THE LIGHTING LOAD—ITS CHARACTERISTICS AND DEVELOPMENT

By W. J. JONES, M.Sc.(Eng.), Member.

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SUMMARY

The author discusses the growth of the lighting load during recent years, and directs attention to the trend in its characteristics for various uses. It is shown that, while the demand for lighting consumption is increasing, there is a simultaneous improvement in load factor. Proposals are put forward for developing the lighting load, and especially opportunities for obtaining increased revenue per pound of capital expenditure by encouraging higher lighting levels and their more extended use. The author urges the appointment of lighting development officers to call at regular intervals on shops, factories, hotels, etc., offering suggestions to improve lighting conditions. It is claimed that the added revenue obtained from giving such services more than meets the expenditure involved. An estimate is given of the potentialities of the lighting load in Great Britain, assuming reasonable increments in lighting levels.

INTRODUCTION

The electricity supply industry was founded partly on the demand for electricity as a motive power in works, but more generally for its use in providing artificial light. Factories were in the nature of wholesale users of electricity with a demand throughout the year, while the majority of lighting consumers only required electricity as a means of providing a substitute for daylight.

The lighting demand coming simultaneously with the power demand in winter afternoons gave rise to a peak demand on the supply undertakings' busbars. Both demands, however, were responsible for the peak, the one taking cheap units all the year round, and lighting being responsible for a much smaller number of units at much higher prices. At an early date investigations into the economics of electricity supply suggested filling up the valleys caused by these demand peaks, or, alternatively, of attempting to limit the peak in order to improve the economic efficiency of the plant. Many supply engineers overlooked the fact that a load with pronounced peaks, when paid for on an economic basis, enabled cheap units to be supplied at other times of the day. The search for "off-peak" load encouraged supply engineers to build the heating and cooking load, and the last 10 years has witnessed phenomenal activity on the part of the supply industry in this country to develop electric heating and cooking. Showrooms have been adapted to facilitate cooking demonstrations, special staff engaged to give demonstrations, and canvassers and service men and women appointed to seek business. So far as domestic heating and cooking is concerned, Great Britain has little to learn from other countries. It is the author's considered view, however, that endeavours to promote the use of electricity for all purposes do not absolve the supply industry from engaging in the systematic development of lighting. In many areas, present lighting development has been due more to the percolation of national propaganda than to positive development forces locally.

The remarkable progress made in recent years makes it necessary to obtain a fresh perspective of the lighting load and its potentialities. The opinion that electric light is a poor substitute for daylight must be revised as it does not accord with the views of the commercial world. This paper attempts to estimate the magnitude of the lighting load, its characteristics and its probable trend, given a reasonable development programme.

THE PRESENT POSITION

Table 1 indicates the number of potential lighting consumers in Great Britain, and also the number of domestic premises at present connected to the mains, which it will be noted represents two-thirds of the total. The rate of connecting domestic premises has accelerated during the last few years, but, bearing in mind the fact that last year

Table 1

LIGHTING CONSUMERS IN GREAT BRITAIN, 1935–36*

Type	Number	Number connected	Percentage connected	Average consumption per consumer	Revenue per consumer	Average price per kWh
	Millions	Millions	%	kWh	£	d.
Domestic premises	10·937	6·484	59	500	3·64	1·75
Commercial premises } Power consumers }	1·943	1·168	60	2 300	19·3	2·01
				—	—	0·51–0·79
Total	12·880	7·652	59·4			

* Seventeenth Annual Report of the Electricity Commissioners, 1936–7.

no fewer than 350 000 new houses were built, one is reminded that the progress in domestic electrification must be maintained at 1 million per annum if the bulk of domestic premises are to be on the mains within the next 5 years.

Table 2

COMMERCIAL LIGHTING

Premises	Number
Retail shops	750 000
Factories, workshops, etc. (under Home Office Regulations) ..	546 303
Schools	46 018
Cinemas	4 700
Theatres	2 000
Hotels, restaurants, boarding houses	70 000
Public houses	55 000
Churches	60 000
Railway stations (including goods)	13 695
Offices and warehouses	Number unknown
Public buildings	Number unknown
Traffic signal crossings (4 000 000 kWh per annum)	2 350
Telephone boxes (1 947 000 kWh per annum)	48 000
Street lighting posts (electric and gas)	850 000

The more remunerative domestic lighting consumers are already connected to the mains. It is not long since some engineers expressed the opinion that the remaining small lighting consumers would not justify the capital expenditure involved in connecting them to a public supply. A study of the economics of the situation has proved this opinion to be incorrect, since these small consumers in densely populated areas represent a surprisingly large consumption and revenue per mile of feeder. Furthermore, the longer the consumer has an installation, the higher the consumption. In Sunderland, for example, the average consumption for domestic consumers of the assisted wiring class has increased from 175 units per annum to 341 units per annum in 2 years. Investigations in the United States of America and Germany indicate similar experience.

Table 2 sets out the main sections of non-domestic lighting consumers, which, for convenience, are referred to generally as commercial lighting consumers. In addition, there are those factories in which lighting consumption is included with power.

Among the miscellaneous uses is included the recently developed lighting load for traffic signals (2 350 sets in the country), representing a consumption of 4 000 000 kWh per annum; and the lighting of telephone boxes (numbering 48 000), with an annual consumption of 1 947 000 kWh.

Then, too, there are the lighting of aerodromes for night flying; horticultural applications; festival lighting for health resorts; and floodlighting, which now represents a popular feature throughout the country.

A partial estimate of consumption for lighting purposes in this country at the present time, derived from the engineering and financial statistics of the Electricity Commission, 1935–36, is given in Table 3.

It will be noted that lighting provides 77 % of the revenue under the above heading and accounts for 57 % of the consumption. If street lighting is included, there is the remarkable fact that, excluding electricity used for lighting on power or traction supplies, 50 % of the total revenue obtained by supply undertakings is derived from the sale of electricity for lighting purposes. The estimates of revenue are conservative, since the realized price for heating and cooking units is taken at 1d. and it is well known that tariffs of ½d. or ¾d. are prevalent.

From further subdivision it would seem that at least 32 % of units sold for lighting, heating, and cooking purposes are used for lighting shops, small factories, offices, schools, etc.

Recent studies show that an upward trend in lighting level is accompanied by an improvement of load factor—the higher the standard of lighting the more hours it will be used per annum. This is because artificial light is not used until it is better than the daylight available. Better artificial light, therefore, means later "switching off" in the morning and earlier "switching on" in the afternoon. Apart altogether from this fact, attention should be given to the influence of changes in building construc-

Table 3

CONSUMPTION AND REVENUE FROM THE SUPPLY OF ELECTRICITY FOR LIGHTING, HEATING, AND COOKING

Use	Consumption	Revenue		Price per kWh
	kWh × 10^6	£ × 10^6	%	d.
Domestic lighting	1 400	34·08	77	2·6 (derived)
Commercial lighting	1 750			
Heating and cooking	2 355	9·99	23	1·00 (assumed)

NOTE.—The average consumption per domestic consumer in the United States is 700 kWh per annum, of which 350 are estimated as lighting consumption. The average lighting consumption per commercial consumer is given as 3 000 kWh per annum. For Great Britain the corresponding figures are 500, 200, and 2 300, respectively.

tion and the requirements of certain consumers. For example, those responsible for rebuilding schemes in congested areas find it impossible to provide adequate daylight in the innermost parts of rooms for much of the year, and this involves supplementary artificial lighting. Shopkeepers, when reconstructing shop fronts, often obtain added window display space by having deep re-entrant windows. This, together with the knowledge that artificial lighting helps to sell goods, results in these premises taking electricity supplies during many hours of daylight.

DOMESTIC LIGHTING

Table 4 refers to the growth of lighting consumption in mixed groups of houses in two districts of North London:—

Table 4

Year	Hendon houses (approximately 100)		Finchley houses (approximately 100)	
	Average annual consumption per house	Percentage of 1922 consumption	Average annual consumption per house	Percentage of 1922 consumption
	kWh		kWh	
1922	279	100	228	100
1924	328	118	286	125
1926	348	121	385	168
1928	363	134	403	177
1930	428	153	459	201
1932	425	152	448	197
1934	475	170	522	229
1936	706	253	531	233

Householders are gradually adopting 75- and 100-watt lamps in preference to 40- and 60-watt lamps. This is noticed in the sales of electric lamps, there being a steady increase in the average wattage of lamps sold in this country. It will be noted from Table 4 that the consumption for domestic consumers in Hendon and Finchley has doubled in the last 12 years. Equally interesting is an aspect of domestic lighting consumption in Croydon, Sunderland, and Blackburn (see Table 5). A weekly charge is made in each case and a certain number of units are provided without extra charge. The average consumption is much higher than that assumed for the country as a whole (see Table 3), while over 70 % of the consumers exceed the allowance of "all in" units.

Table 5

Town	Scheme	Number of consumers	Units supplied free	Payments collected	Customers exceeding unit allowance	Average consumption
					%	kWh
Sunderland	Assisted wiring*	7 279	240	Weekly	70	341
Blackburn	Assisted wiring*	3 676	260	Weekly	70	299
Croydon	Assisted wiring*	9 800	168	Weekly	88	346

* In these schemes wiring, lamps, and an iron, were provided free, additional units being supplied at ½d. or ⅓d. Instead of reducing the unit charge from time to time the number of free units has been increased. This still further increases consumption.

A study of the load curves of a number of undertakings, of which those for Hull and Sunderland are typical, reveals the interesting fact that the average maximum demand per domestic consumer for lighting purposes approximates 150 to 200 watts,* and it is conceded that the average consumption for domestic lighting purposes in these towns is at least 150–200 kWh per annum (see Table 6).

This means that the hours use per kilowatt demand must be of the order of 1 000 per annum, and that the annual load factor approximates 12½ %.† These figures are substantially higher than those obtaining a few years ago, and the increase is undoubtedly traceable to the use of higher standards of lighting and increased hours of use. Radio, especially in rural and suburban areas, has encouraged increased use of lighting, while the prevalence of 2-part tariffs with a small secondary charge is encouraging a freer use of light. Radio sets and the extended use of small accessories also account for some of the additional consumption.

Table 6

Town	Number of domestic consumers	Estimated domestic lighting max. demand, summer Sunday night	Demand per domestic consumer	Average annual lighting consumption
		kVA	kVA	kWh
Sunderland ..	15 000	3 000	0·200	200
Hull	67 000	11 000	0·150	150

SHOP LIGHTING

There has been a phenomenal growth in shop lighting during recent years. Fig. 1 is typical of the increased consumption for a row of small shops in suburban areas. Increases of 16 to 20 % per annum are not uncommon for the whole of a shopping district. The experience of the Antrim Electricity Distribution Co. is also interesting. Fifty shops, excluding multiple stores, in 6 small towns showed practically no increased consumption during the first year of supply, but during 1936–7 the increase was 16·1 %. Table 7 reveals the remarkable increases

* Deduced from Sunday evening load curve and number of consumers (see Table 6).

† Woodward and Carne estimate the annual domestic lighting load factor for groups to be between 18 % and 22 % (see *I.E.E. Journal*, 1932, vol. 71, p. 852).

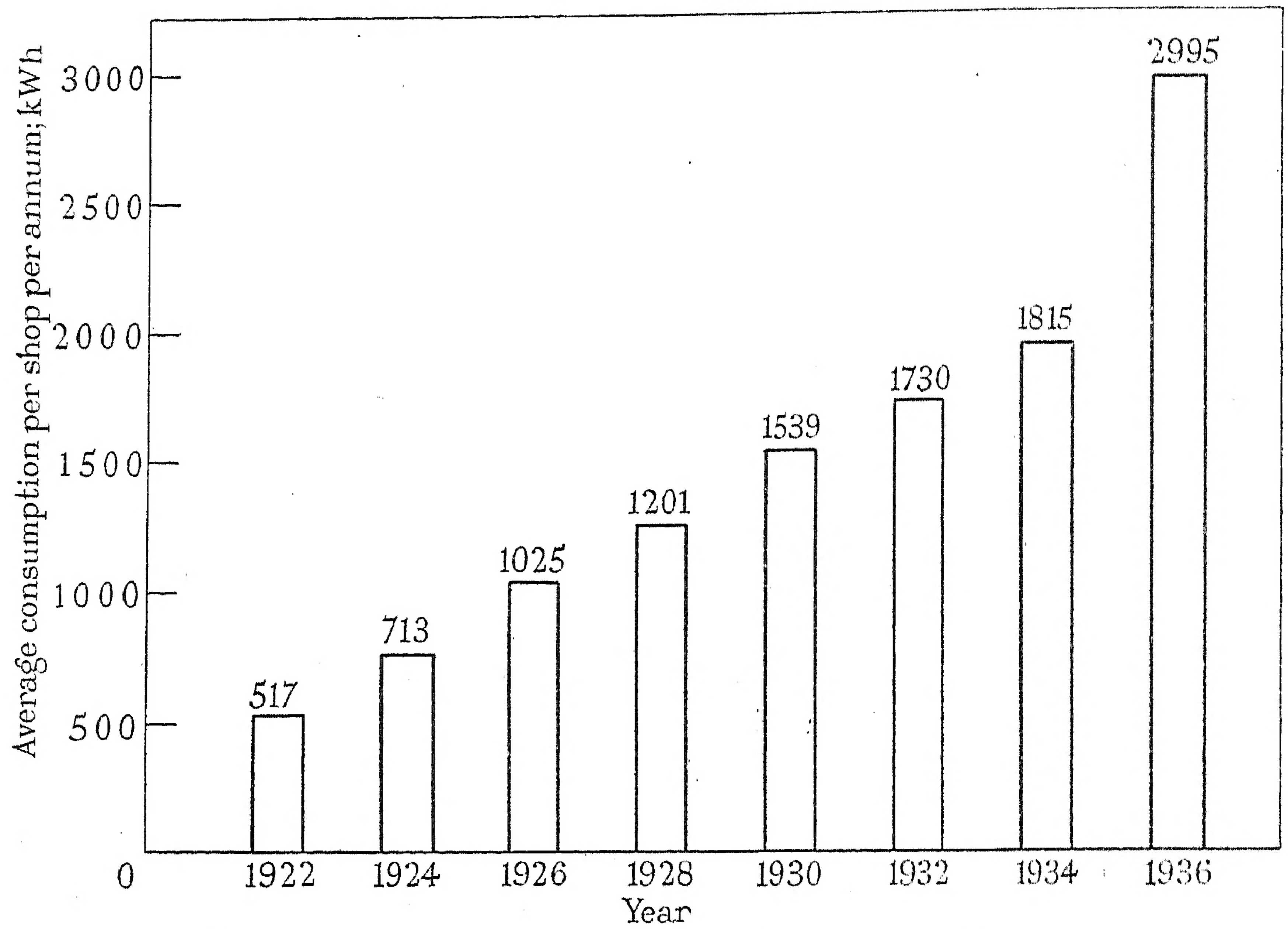

Fig. 1.—Increase in shop lighting at Hendon, 1922–36.

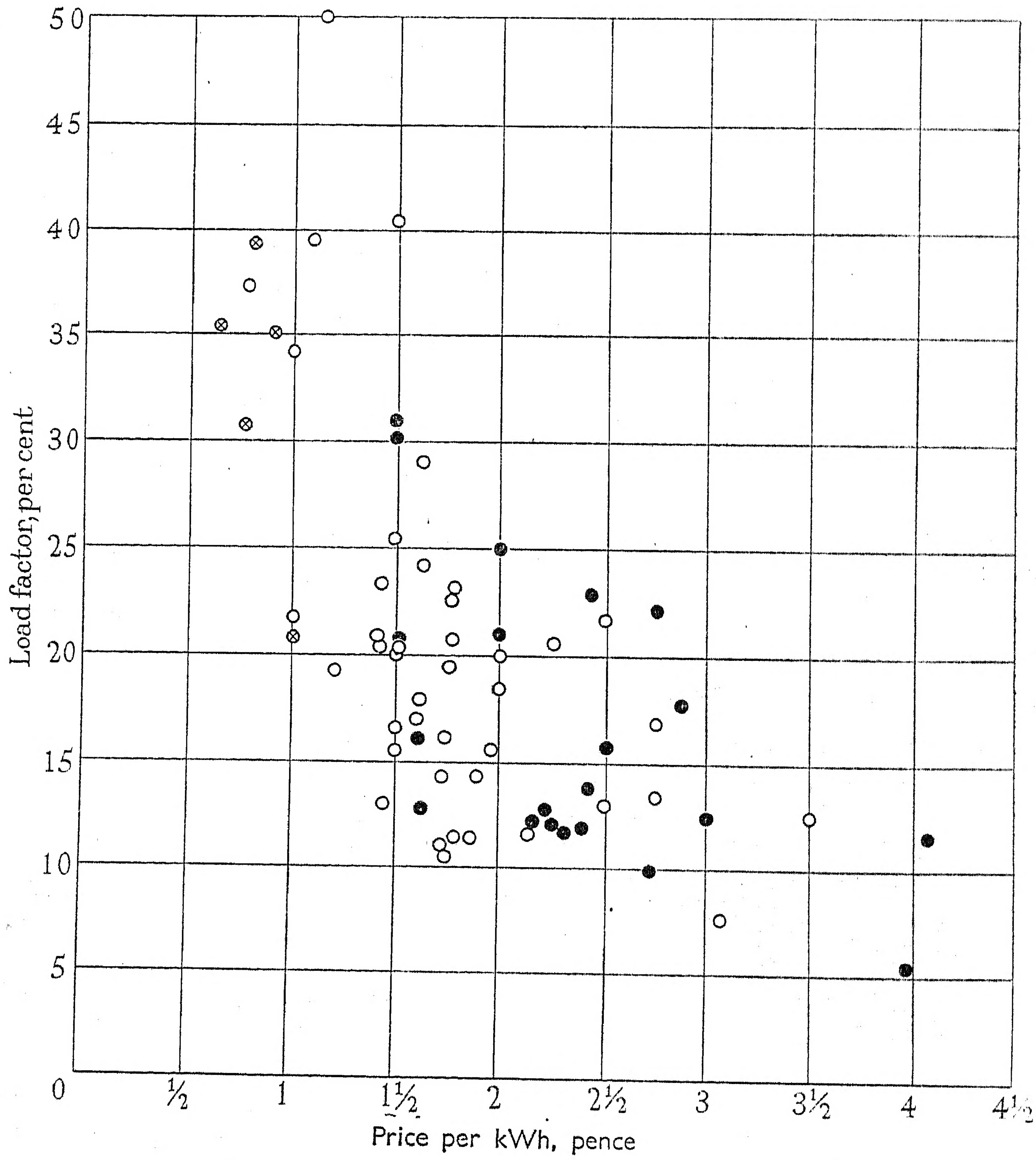

Fig. 2.—Load factor of 70 departmental stores.

● 50–100 kW maximum demand.
○ 100–500 kW maximum demand.
⊗ Over 500 kW maximum demand.

associated with different kinds of shops. The author urges supply engineers to compile similar data and statistics from their own records.

It should be recognized that an improvement in load factor has taken place with the improvement in shop lighting. Fig. 2 shows the load factors of 70 departmental stores plotted against the price per kWh. A further survey in 1936 shows that a sample of 24 of these stores had received reductions in price per kWh amounting to 20 %, and that the load factor of the group had improved by 10 %. One is led to the view that many of these stores are paying amply for the electricity used, bearing in mind the long hours' use of the load. Dr.

Table 7

INCREASE IN CONSUMPTION OF SHOPS

Type of shop	Gloucester, 55 shops		Brighton, 64 shops		Islington, 34 shops	
	Consumption		Consumption		Consumption	
	1921	1933	1922	1933	1922	1933
	kWh	kWh	kWh	kWh	kWh	kWh
13 Bakers	744	3 800	640	1 821	2 232	3 752
17 Boots and shoes	520	2 069	1 178	2 848	1 932	3 572
19 Butchers	390	1 120	625	1 649	3 364	4 742
14 Chemists	1 226	5 190	454	1 580	1 599	1 749
18 Drapers	6 150	62 323	2 667	11 777	947	1 550
17 Grocers	715	2 480	706	1 228	1 632	2 354
15 Men's outfitters	616	2 180	1 116	2 046	1 502	5 670
12 Furnishers	906	6 955	1 389	11 551	2 374	7 962
13 Ironmongers	651	1 604	501	1 313	471	2 272
14 Jewellers	543	3 116	1 340	2 147	2 080	3 826

Most of this increase in shop lighting has been due to improvements in windows and window lighting. Surveys of shop windows in 1925 and 1934 indicated that the wattage per frontage had increased by 150 % in the 9 years under review. The largest field of shop lighting, namely, the adequate lighting of interiors, has made much less progress.

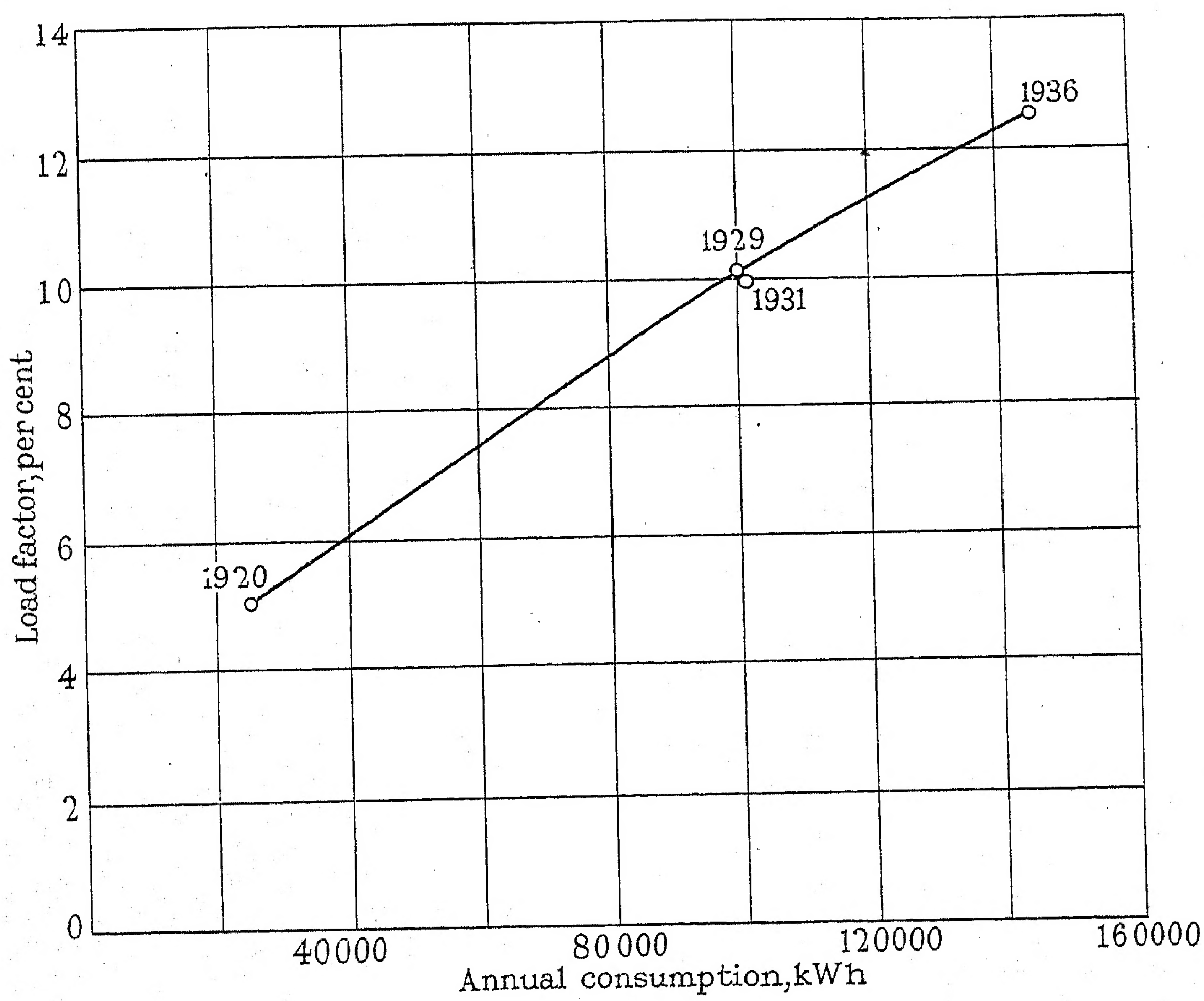

Fig. 3.—Increase in lighting for 50 Cheltenham shops.

Table 8

CITY OF LONDON ELECTRIC LIGHTING CO., LTD.

Year	Number of consumers	Connected load	Units sold	Units per kW of max. demand	Load factor	Proportion of lighting revenue to whole
		kW			%	
1934	19 548	35 452	37 744 660	1 330	15·18	60·3
1935	19 593	36 245	41 993 094	1 448	16·53	58·3
1936	20 087	37 388	44 785 587	1 497	17·1	56·6

Adolph,* basing his conclusions on his experience with the Berlin supply undertaking, makes the following important statement on the question of tariffs for commercial premises: "As lighting represents generally only a relatively small percentage of the total costs of running a business, a prohibitive tariff policy does not materially alter consumption at the peak-load time. Tariffs which are favourable to lighting consumption encourage consumption outside peak time and thereby improve the load curve."

Fig. 3 shows experience in a group of 50 shops at Cheltenham, in which maximum-demand indicators are installed. With a 15 % increase in kilowatt demand between 1931 and 1936, the consumption has increased more rapidly and the load factor has proportionately increased. The advent of the 2-part tariff makes it increasingly difficult to follow these trends with certainty, but the experience of the City of London Electricity Supply Co. appears to be conclusive. The area mainly comprises shops, offices, and warehouses, the two first-named seldom being lighted after closing time as the City of London is deserted when the offices close down. Under such conditions one would expect a poor load factor from lighting. It is interesting to note the improvement in the standard of lighting during recent years, and that, while the lighting consumption has increased, the load factor has improved by 12 %. This example is quoted to show that even under the worst conditions development of lighting is advantageous from engineering and economic points of view (see Table 8).

Table 9 gives the consumption in 1921 and 1936 of some typical business premises in the City of London.

The author suggests that engineers should concentrate on obtaining detailed statistics relating to consumption before and after rebuilding schemes have been put into operation. New buildings invariably include radical improvements in lighting, which result in greatly increased consumption.

Such experience is not confined to this country, since Seeger† has shown that in Germany and France increased lighting demand results in increased hours of use per annum. One cure for a commercial lighting peak is clearly that of encouraging higher standards of lighting in shops and stores.

Returns from 179 departmental stores reveal for 1932 a consumption of no less than 53 million units, 15 of the largest being responsible for half this amount. It is evident that a substantial increase in consumption has taken place since that date.

* "The Light Demand as an Economic Factor," *I.M.E.A. Journal*, October, 1935, p. 164.
† "Lighting Consumption in Europe," International Commission on Illumination, July, 1935.

Table 9

EXAMPLES SHOWING CONSUMPTION IN INDIVIDUAL CASES

	1921	1936
	kWh	kWh
Printing and allied trades		
1	2 284	55 530
2	37 018	275 981
3	36 589	25 906
Catering		
1	41 961	110 627
2	752	7 311
3	1 491	9 192
4	5 496	21 637
Men's outfitters		
1	24 755	59 133
2	3 765	18 801
3	2 561	11 104
4	5 344	60 480
5	9 896	39 190
Manufacturers		
1	8 965	1 415
2	21 575	62 064
3	7 532	75 602
4	7 734	28 569
Jewellery trade		
1	13 140	45 417
2	12 113	105 231
Warehouses, banks, and insurance companies		
1	8 946	72 248
2	8 062	169 222
3	13 064	19 576
4	16 998	41 368
5	4 681	15 998
6	47 607	40 446
7	14 960	26 628
8	41 248	11 746
9	6 110	54 664
10	2 211	29 396
11	22 100	15 932
12	17 921	14 252
Rebuilding (after 1921)		
1	890	20 208
2	11 024	76 274
3	2 742	8 894
4	13 887	70 686

It is not the large retail stores, however, that require regular advice on lighting matters. These stores in some ways set the pace. The small shops can well do with advice from the electrical industry. Many interiors are still lighted with less than 1 watt per square foot. An ordinary shop requires at least 2 watts per square foot for general lighting, with as much again for lighting showcases and displays.

Diversity of lighting load

Contrary to common belief, there is considerable diversity in some types of lighting load. Woodward and Carne give a diversity factor of 2 : 1 for domestic lighting, probably due to the increasing tendency of the public to spend some evenings at friends' houses or at cinemas (curiously enough the Sunday night lighting demand in many areas shows little diversity).

Off-peak lighting loads

Clearly, too, certain forms of lighting load occur at off-peak periods (assuming the normal peak period to be between 4.30 p.m. and 5.30 p.m. in November). First in this category come public-houses. The 70 000 licensed premises in this country are not allowed by law to be open during the period 4.30 p.m. to 5.30 p.m., and hence all their lighting consumption is off-peak. Although improvements in public-house lighting during the past 5 years have been remarkable, these premises still offer an important opportunity for load-building.

Table 10

LIGHTING LOAD CHARACTERISTICS

Type of load	Load factor (individual)	Approximate hours' use per annum	Percentage demand at station peak
	%		
Domestic ..	10	800	50
Retail shop ..	10–30	800–2 400	100
Factory:—			
1 shift	5–12½	400–1 000	100
3 shifts ..	60	4 800	100
Cinemas	10–20	800–1 600	Up to 100
Public houses ..	10–15	800–1 200	Nil
Schools	2½	200	Nil
Churches ..	2	160	Nil
Street lighting:—			
Half night ..	22	1 800	
All night ..	50	4 000	100
Traffic signals ..	Up to 100	Up to 8 700	100

Similarly, school lighting is for the most part off-peak. School finishes before 4.30 p.m., and even where the school is used for evening classes these do not commence until 6 or 7 p.m. In spite, therefore, of the fact that the hours of use per annum for school lighting are small, this type of load is profitable to the undertaking. The Board of Education's recent recommendation* of 10 foot-candles in classrooms is for approximately double the amount obtaining to-day. Lighting for churches and halls is also required at a later hour than the usual peak time.

* "Elementary School Buildings," p. 99.

Cinemas

Cinemas constructed 12 years ago had little vestibule space, the maximum area being allotted to the auditorium, where lighting was used only between pictures. To-day, however, cinemas are built with vestibules and restaurants occupying a much bigger proportion of the total floor area, and these areas use light continuously all the time the premises are open. This is reflected in the load factor, that of newer cinemas being as high as 20 %, while that of older premises approximates to only half this value.

Illuminations

Then, too, illuminations at health resorts provide interesting data, headed with the amazing spectacles at Blackpool and Southend, totalling a demand of 4 000 kW. These illuminations, in extending the season, assist the general sale of electricity, and it should be recognized that this demand is clear of the autumn peak on which the "grid charges" are made. Units sold for this purpose represent valuable additions to revenue, while the cost is little more than the unit rate of supply.

Before dismissing the question of demand at station peak, it is well to remember that cooking, in some districts, is causing the major peak, and for this reason some engineers are beginning to reconsider the possibilities of lighting generally as an off-peak load for their undertakings.

ELECTRICITY TARIFFS

Because grid charges are made on a 2-part basis, there is no inherent reason why lighting and domestic consumers should be charged on the same basis. The 2-part tariff does, however, provide a good foundation for steady income and a psychologically good incentive for increased consumption. There does not appear, however, to be any justification for assessing the fixed charge for lighting on a kVA basis, so far as the consumer is concerned. It matters little if the computation of the charge is made in this way for internal purposes, although this may be challenged on the score of equity by some classes of lighting consumers, but the kVA basis, or its equivalent number of lamps, should be rigidly excluded from negotiations with all except very large consumers, since it imposes an unnecessary restraint on the installation of additional lighting. The author concedes that in some shop lighting the introduction of a 2-part tariff with the fixed charge based on the installed load has resulted in increased consumption, but his general experience leads him to the view that the tariff with the kVA basis for the fixed charge handicaps progress.

The author does not favour a uniform type of tariff for all classes of lighting consumers. By modification of a tariff to suit a given set of conditions, the undertaking can obtain revenue not otherwise possible. By all means have a simple uniform tariff for domestic consumers and for the basic lighting requirements of small shops, but undertakings should safeguard the right to give appropriate terms for special requirements.

Mr. J. N. Waite has afforded the author an interesting example of flexibility in tariff negotiations. A certain public-house within the Hull area of supply installed an entirely new system of architectural lighting, the demand

being 15 kVA instead of the 3 kVA obtaining previously. After the first year the consumer cut down his lighting by 30 % on the score of cost. Realizing that the load never came at the peak period, Mr. Waite modified the method of charge so as to encourage the retention of the full lighting system. Similarly, much can be done by encouraging display lighting, floodlighting, and electric signs, at terms approaching $\frac{1}{2}$d. or 1d. per unit, provided the use continues from dusk to midnight, with a possible limitation of " switching on after 6 p.m." when required. A general restriction clause " after 6 p.m." in the case of, say, floodlighting from dusk to midnight, represents a reduction of 12 % on the units which would be taken if the proposals outlined by the author were adopted.

INDUSTRIAL LIGHTING

There are 546 303 premises throughout the country which come under the Home Office regulations, but the value of the lighting load in industrial premises is masked by the fact that lighting units are frequently included in the power consumption. Consumption varies widely according to the type of the premises, the nature of the work, and the economic conditions prevailing. For example, a multi-story factory costs more to light per annum than a single-story building with a north-light roof, although the latter costs more to warm and keep cool. Plant with overhead gear, such as is used in the textile industry, involves prolonged use of artificial light, even during daytime. Also there are factories which are engaged on work involving day and night operation. Artificial lighting conditions in factories regularly receive the careful consideration of H.M. Inspectors of Factories, and now that the Factory Act, 1937, gives mandatory powers to the Home Office to require prescribed standards of lighting, there is a likelihood of more rapid improvement in lighting conditions. Many large industrial concerns already provide proper lighting, but in the smaller factories, and especially in older buildings, lighting conditions are still far from satisfactory. The 1937 Factory Act comes into operation in July, 1938, and the Departmental Committee on Factory Lighting set up by the Home Office is at present considering standards of lighting in connection with the working of this Act. Recent investigations show to what a remarkable extent industrial lighting could be developed on economical grounds, although it is probable that " welfare " considerations will have greater force in future development.

STREET LIGHTING

Fig. 4 shows the growth of electricity used for street lighting during the years 1923–1935. This growth is due to:—

(1) Improvements to existing public lighting.
(2) The provision of public lighting in new housing estates and in villages previously without public lighting.
(3) Conversion of gas-lighted posts to electrically-lighted posts.

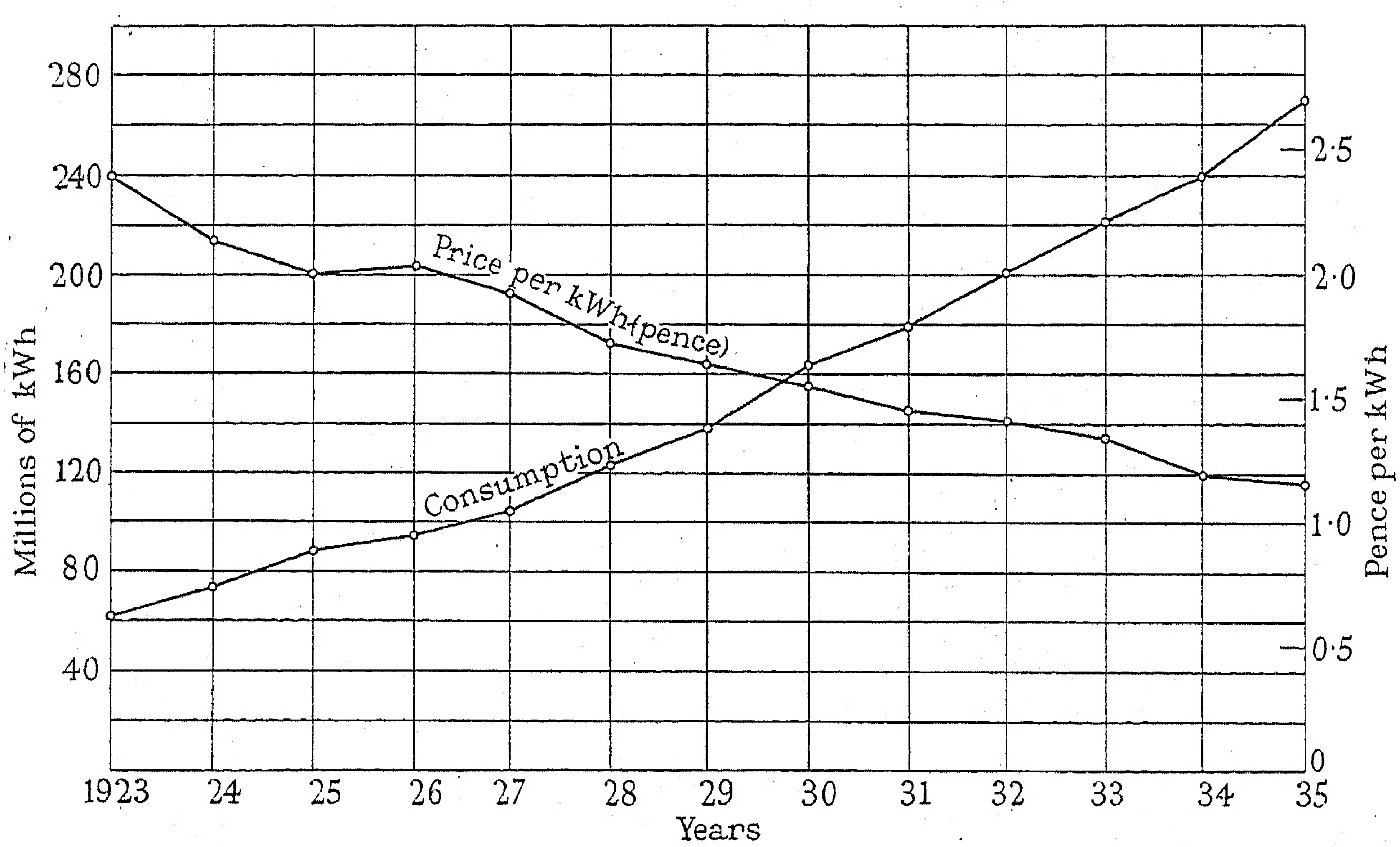

Fig. 4.—Increase in public electric lighting in Great Britain, 1923–35.

Investigations into the light output of gas burners, and a study of the economics of electric street lighting,* provided data for meeting gas ecompetition, and this, together with the advent of the electric discharge lamp, has resulted in some 1 500 miles of street lighting being changed from gas to electricity during the past 3 years.

The provision of electric street lighting where none existed previously accounts for a similar increase in mileage lighted. In spite of remarkable advancements during recent years, much of the existing electric street lighting (particularly in side streets) is out of date, and, furthermore, there are some 500 000 street lamps still lighted by gas. Allowing for the possible use of electric discharge lamps, the author estimates the potential consumption of electricity for public lighting at $1\,100 \times 10^6$ kWh per annum.

* J. N. Waite and W. J. Jones: *Proceedings of the I.M.E.A.*, 1932, p. 64.

NEW LIGHT SOURCES

The question will naturally be asked: "What of the new light sources and the lighting load? Will not the advent of light sources 3 to 5 times more efficient than tungsten lamps cause a falling-off in lighting consumption and corresponding loss of revenue?" The author believes that such a danger is only likely with a passive development policy. So far as domestic lighting is concerned, the adoption of a universal 2-part tariff safeguards the position, but more active steps are required to make the 2-part tariff universal. To achieve this ideal, the adoption of the 2-part tariff must show an advantage to existing lighting consumers. The general adoption of a 2-part tariff can be brought about in the following ways:—

(1) By giving the consumer no option. This is tantamount to raising the price of electricity for lighting.

(2) By lowering the fixed charge and/or secondary charge. This will often represent a loss of revenue which cannot be contemplated.

(3) By actively promoting increase in lighting. This automatically brings the consumer to a position where he will find it advantageous to go over to the 2-part tariff.

Alternative (3) appears preferable as it converts the small consumer into a more profitable consumer and provides the extra revenue for financing the promotional activities.

So far as commercial consumers are concerned, each improvement in the luminous efficiency of light sources has coincided with increased consumption, but undertakings cannot expect this remarkable situation to be maintained in the future without positive promotional efforts.

ACTIVITIES TO PROMOTE INCREASE IN LIGHTING IN AMERICA

The author recently had the opportunity of studying lighting-promotion activities in the United States and Canada. Undertakings make an economic approach to the problem by estimating the cost of adding load to produce 1 dollar of earned annual revenue. The fact is recognized that load increments bring in revenue year after year and for this reason justify promotion expenditure approximating 50 to 100 per cent of the first year's revenue from the added load. The economic advantage of promoting commercial lighting is found to be such that central stations can obtain $1 earned annual revenue at a cost of 50 cents. The cost of promoting home lighting approximates one dollar per dollar of earned annual revenue.

The development officers employed on commercial lighting have some knowledge of lighting but are not necessarily engineers. They are chosen primarily for their commercial ability, since they may always obtain the expert assistance of lighting engineers from headquarters. The lighting departments also employ specialists for liaison work with architects. Many undertakings employ one lighting salesman per 1 000 commercial consumers (comprising shops, offices, workshops, schools, churches, cinemas, hotels, etc.), and the salesman is expected to call on all commercial consumers in his territory at least once in two years, and those representing better prospects once or twice a year. He is expected to make himself responsible for adding 200–250 kW per annum.

Assuming that a lighting development officer in Great Britain added 100 kW of commercial lighting per annum, then at 10 % load factor and 2d. per unit this increment in load would produce an earned annual revenue of £730—sufficient to pay the salary of two salesmen at present rates of pay prevailing in supply undertakings.

Home-lighting advisers

Of almost equal interest is the organized effort in the U.S.A. to improve domestic lighting. Supply undertakings have 1 800 home-lighting advisers on their staffs to call at homes and, with the help of simple demonstrations, give suggestion for improvements in lighting. Already 2 million homes have been called on in this way. Compare this with our own practice of never going near the bulk of our domestic consumers unless a fuse blows, or unless it is necessary to discuss a new tariff. Our main contact between supplier and consumer is the sending of a bill once a quarter.

A typical lighting department

Fig. 5 shows the organization chart of the Lighting Department of the Buffalo, Niagara, and Eastern Power Corporation, while particulars of the areas covered and the results obtained are given below.

Similar information is given in the Appendix for other districts, varying from the large Chicago undertaking to a small undertaking at the lakeside town of Sandusky.

The author believes that similar organizations, suitably adapted to British conditions, could well find a place within the commercial operations of electricity supply in this country.

Buffalo, Niagara, and Eastern Power Corporation

Town	Population	Staff on lighting promotion
Buffalo	500 000	10 for commercial lighting; 2 for industrial lighting; supported by 4 engineers in office for preparing plans, etc.
Batavia	35 000	1 man
Bradford ..	25 000	1 man
Niagara	75 000	3 men
Olean	35 000	1 man
Tonawanda ..	25 000	1 man
Semi-rural areas	9 000 homes	3 men

Results:—

Load added: 200 kW per man per annum.
Revenue: $6 000 per man per annum.
Average revenue per unit in Metropolitan area, 1·8 cents.

Average revenue per unit outside Metropolitan area, 2·4 cents.
Earned annual revenue per kW added works out at $35 for commercial lighting.
Earned annual revenue for kW added works out at $22 for industrial lighting.

Home-lighting promotion.

Staff. 18 home-lighting advisers.
One girl prepares plans for builders and special customers at rate of $1\frac{1}{2}$ plans per day.
Each adviser makes 500 home-lighting demonstrations per annum.

Revenue. Average revenue per unit in Metropolitan area, $1\frac{1}{2}$ cents.
Average revenue per unit outside Metropolitan area, $2\frac{1}{2}$ cents.

Results. 165 kW per girl per annum, representing an increase of annual consumption of 125 000 units per annum per adviser, and an extra annual revenue of $1 800 per adviser in the Metropolitan area and $3 000 per annum outside the Metropolitan area.
Experience shows that neighbours of households adopting recommendations increase their lighting by 75 %. The load increase may therefore be estimated at three times that actually installed.

POTENTIALITIES OF LIGHTING LOAD

The full economic expansion of electrical services can be attained only when the consumer recognizes his needs and is shown the means of meeting them. There is ever-increasing competition to secure a share of the consumer's income, and for this reason alone the electrical

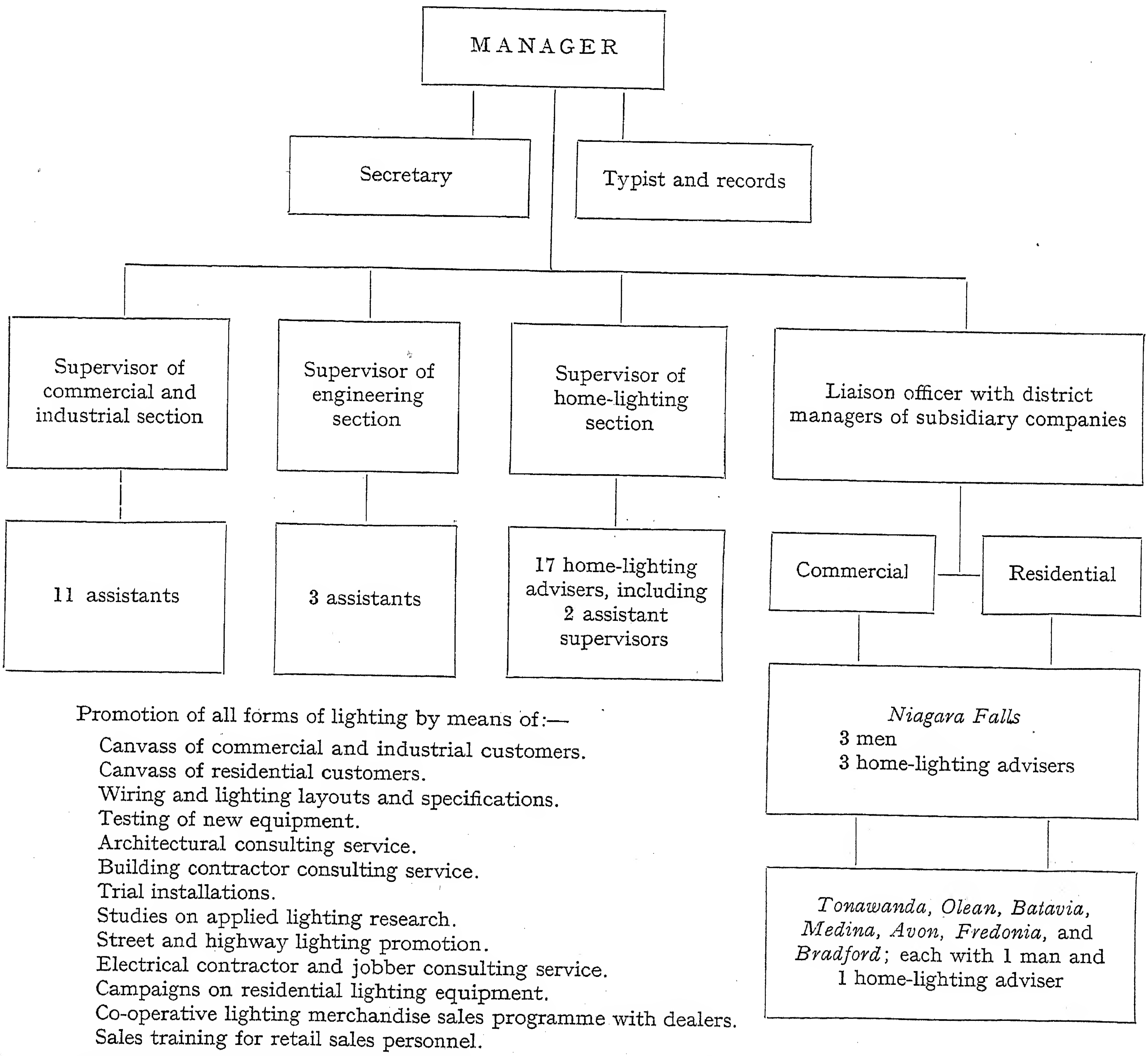

Fig. 5.—Organization chart of lighting sales department, Buffalo, Niagara, and Eastern Power Corporation.

industry cannot afford to take what comes, but must itself seek expansion within the economic limits.

Capital and time have been expended in connecting the consumer to the mains, but it should be recognized that the present consumption can be readily doubled or trebled.

Table 11 summarizes the potentialities of lighting consumption, assuming moderate increases over that prevailing, and the author believes that the promotion of the lighting load represents an important means of obtaining more revenue per £ of capital expenditure.

Table 11

	Present consumption	Objective consumption
	kWh × 10^6	kWh × 10^6
Domestic	1 400	5 500
Commercial	1 750	6 800
Industrial	800	3 200
Street lighting	271	1 100
	4 221	16 600

A check on 50 000 people asked to choose how much electric light they would like to have for reading revealed an average figure some 20 times greater than is commonly used. While there is an obvious limit to the consumption of electricity for heating and cooking, the principal limit of consumption for lighting purposes—whether for utility or decoration—is an economic one. There is everything to be gained by developing all uses of electricity, but this should not warrant the neglect of the economic expansion of the load which at the present time provides such a large proportion of the total revenue accruing to supply undertakings.

Finally, the author desires to thank all those who have helped in the preparation of this paper by providing data.

APPENDIX

LIGHTING-PROMOTION ORGANIZATIONS IN VARIOUS AMERICAN TOWNS

Ohio Public Service, Sandusky

The population is 28 000. Of these, 7 000 are domestic consumers with an annual consumption of 720 kWh, and 782 commercial consumers, with a consumption of 4 392 kWh.

The lighting service staff consists of one man with a salary of \$100 per month, plus commission on sales of fittings. In 1936 he earned \$5 000.

The load added in 1936 was 446 kW of commercial lighting.

The promotion of school lighting in this town is of special interest. The education authority has installed lightmeters in 140 classrooms, and teachers are instructed to switch on the lights when the lightmeter records less than 15 foot-candles.

Montreal Company Operating outside City

Town	Population	Lighting development staff
Three Rivers	30 000	2 men, 1 girl
Valley Field	10 000	1 man
Victoria Ville	7 000	1 man
Shawana Falls	15 000	1 man

In the smaller towns the men do promotion work for both commercial and domestic consumers.

Each kW added for commercial lighting brings in \$35 per annum.

Each kW added for domestic lighting brings in \$25 per annum.

Each salesman adds 100 kW per annum.

Salaries and expenses per annum for this work approximate to the added revenue obtained in the first 12 months.

Chicago Edison Co.

Type of consumer	Number
Commercial	125 000
Industrial	15 000
Residential	900 000

Lighting Service Staff:—

14 salesmen on industrial lighting in two areas.
57 salesmen on commercial lighting in five areas.
Lighting engineers on staff for preparing plans, etc.
Staff of "call" men employed for follow-up work.
1 lighting specialist for school lighting.
2 lighting specialists for street lighting.
3 lighting specialists for office lighting.
4 lighting specialists for liaison with architects.

Each commercial lighting salesman makes an average of 6 calls per day.

The department installs up to 12 fittings for one month as a demonstration.

150 lightmeters are available for loan to consumers

[The discussion on this paper will be found on page 300.]

DISCUSSION BEFORE THE INSTITUTION, 10TH MARCH, 1938

Mr. J. W. J. Townley: I do not agree with the author's statement on page 290 that "It is not long since some engineers expressed the opinion that the remaining small lighting consumers would not justify the capital expenditure involved in connecting them to a public supply. A study of the economics of the situation had proved this opinion to be incorrect. . . ." The small working-class consumer in this country who uses electricity for lighting alone provides an average revenue of about 35s. a year, yet it costs well over £2 to supply that consumer with his first unit. I think, however, that the author is referring here to the small consumer who uses electricity not only for lighting but also for other incidental purposes, because he goes on to show how the small consumer in Sunderland has increased his consumption from 175 to 341 units per annum. Such a total clearly includes energy taken for the small incidental uses referred to later in the paper, e.g. wireless (60–80 units a year, equal to the lighting consumption of many small consumers), and an electric iron. Again, it seems to me that the figures for lighting consumption given in Table 4 include uses other than lighting. I should like to emphasize that the small lighting consumer is of no value as such to the supply undertaking. He should be encouraged to increase his consumption by installing other apparatus, particularly a cooker or a water heater.

The type of development mentioned by the author has to be very carefully handled by the supply industry, as, while there may be no limit to a consumer's absorbing power, there is a limit to his purse. Many consumers, I know, would gladly increase their lighting consumption if they could afford it.

I should like to confirm some of the figures given in the paper for the increase in the size of lamps used in recent years, particularly by domestic consumers. I have a large assisted wiring scheme with about 40 000 consumers, and in 1932, out of 57 000 lamps issued under that scheme, 3 % were of 75 watts and over, while in 1937 14 % were of 75 watts and over.

I suggest that supply engineers should include in their assisted or hire wiring schemes for small consumers the provision of lamp replacements, because these consumers will not buy lamps and keep their holders filled. We have found a remarkably large number of installations where there was one lamp only and it was taken from one room to another; this is very unsatisfactory. By the introduction of a maintenance scheme providing for the replacement of lamps without charge, we were able to increase the consumption of these consumers by no less than 20 %.

The subject of tariffs is one which requires a great deal of consideration if we are going to get all the lighting load that is possible. For the large store some form of two-part tariff is satisfactory; because if we can inform the large shopkeeper that all the units he uses after ordinary shop lighting hours will cost him only, say, ¾d. a unit, it is easy to induce him to leave his shop windows illuminated after hours. We lend our show-room windows to local traders during the year for about a fortnight at a time, and we do our best to illuminate their goods satisfactorily. The result has been excellent, because the shopkeepers have said "This looks a great deal better than in my window; what shall I do about it?" At the same time, the development officer must handle his "prospect" with discretion.

Public lighting presents a difficult problem because the lighting of our main highways is in the hands of the local authorities, and an increase in street lighting means an increased charge on the rates. The solution is to induce the borough surveyor and the highways committee to allow a stretch of experimental lighting to be put up entirely at the expense of the electricity supply undertaking, with the promise that it will be taken down if so desired. Once the improved lighting has been put up, owing to the pressure of public opinion the highways committee will not discontinue it, and there usually follows a demand for a general improvement in the local street lighting.

Mr. A. Cunnington: I agree with the author that railway lighting offers a possible field for the development of electric lighting. So far as the Southern Railway is concerned, there has been some development in that direction; 25 years ago 3 % of our stations were electrically lighted, and the figure is now about 20 %. Taking the area within 50 miles of London, where a supply is available at practically every station (in Devon, Cornwall, and elsewhere there are remote country stations where there is no supply), 40 % of our stations have been converted to electric lighting. The change-over has been almost always made on economic grounds, though there may be certain special cases where matters of policy have entered into consideration.

The two-part tariff is very well suited to railway lighting because our average hours of use are fairly long. It is also valuable from the point of view that it enables us to employ electric heating in such a place as a small signal-box at the end of a lighting service.

With regard to the load factor of railway lighting, nearly all our connected load does come on at the peak time, but the average running hours are long, and there is a tendency for all-night lighting to increase, especially in suburban areas, owing to the increased necessity for shunting at night where there is an intensified electric passenger-train service. Our colour-light signals, with approximately 100 % load factor, on the lines of the traffic signals to which the author refers, are another useful load.

An experience which I have had recently with a floodlighting scheme suggests that it is possible to deal with the question of off-peak load to some extent. We had a large scheme of about 100 kW, and although the supply authority were a little concerned about it they were able to offer very favourable terms provided we switched out the floodlighting during the worst peak point in the winter. This did not make much difference, because the advertising value of the floodlighting was mainly associated with the period after 6 p.m., when people were travelling home. A good deal of floodlighting could no doubt be arranged to come on after the peak period in this manner.

I should like to refer to the question of the small

accessories which Mr. Townley quite rightly said could not be classed as lighting, but which are closely allied to it. If facilities for plug connections and built-in fittings were greater, there would be considerable development of the load. The electrical contractor may be to blame here. I can instance the case of a friend of mine who has recently occupied a new house, built on modern lines, about 25 miles from London. He applied for an electric lighting supply and was able to obtain it without difficulty, but the specification which the supply authority put forward for electric lighting included *one* point in the centre of the lounge and *one* plug on the skirting-board near the fireplace. This is what I had 20 years ago, and it is very unsatisfactory to find a modern house so scantily equipped.

I have for some time felt strongly that there is room for considerable development in regard to facilities for small accessories such as table lamps. I do not see why plugs should always be placed on the skirting-board level and behind the furniture, where we have to grovel after them; why should not they be fixed at the height of the dado rail or its equivalent? Table lamps should be supplied with a short, semi-rigid connection like a piece of flexible metallic tube, which could be pushed into a socket, and I should like to see 10 socket-outlets per room instead of one.

I agree with the author's general conclusions as to the potentialities of lighting-consumption development, but I think that to secure such development three things in particular are necessary. Firstly, increased facilities such as I have suggested; secondly, more progressive canvassing; and thirdly—and most important—the universal provision of simpler and more attractive tariffs.

Mr. Forbes Jackson: It is rather difficult for us as electrical engineers to take a detached view of the relationship between the supply industry and the consumer. Our duty as engineers is to use the resources of nature and our consumers' money to the best advantage, but as partners in the electrical industry we are naturally inclined to sell as much electricity as we can. I sometimes feel, when discussing matters with electrical people, that we are apt to forget that we ought to be engineers first and electrical missionaries second. I make this remark because of a sentence in the paper (page 294) to which I should like to call attention: "New buildings invariably include radical improvements in lighting, which result in greatly increased consumption." It is not that at the cost of some increased consumption we can obtain some improvement in lighting; the sense of that sentence is obviously that the desirable thing is the greatly increased consumption. Would any of us buy a motor-car if we read in the prospectus that the manufacturer had introduced some improvements which had greatly increased the petrol consumption?

It seems clear that we are now entering on a phase of greater use of lighting, or possibly greater extravagance in lighting. The electrical industry is clearly the only industry which is concerned in this question, and it has to make up its mind what part it is going to play. Our main contribution to the question of lighting will be concerned with the price that we are going to charge for it. The original lighting tariffs were very clearly related to the cost of giving the supply: there was only the lighting load, and obviously it had to bear the whole cost. Nowadays, however, lighting supplies are being charged rather on the basis of what revenue they will bring in than of what they cost to give. As an example, I have in mind a pumping station where some $2\frac{1}{4}$ million units are being used for power at a load factor of 56 %, and for that I am paying rather over $\frac{1}{2}$d. a unit. Because that station was built very largely underground, the lighting load-factor is also very good, and by a coincidence it happens to be 56 % also. I found, however, that I had to pay $4\frac{1}{2}$d. a unit for lighting; I raised the question with the engineer of the company, who said that he could not reduce the figure below $2\frac{1}{2}$d. because the energy was being used for lighting.

I agree with what the author says about the use of lighting canvassers. I am sure that there is a market for more energy for lighting, particularly in small businesses and in middle-class houses where the desire for a little additional luxury and the money to pay for it are present. In the case of business premises a greater lighting consumption would not embarrass the supply undertakings, because the maximum-demand increase which would follow as a matter of course is already taken care of, the tariff being based either on a measured maximum-demand or on the connected load; but with the domestic two-part tariff, based originally on some assumption with regard to the normal lighting load, there is no means of altering the fixed charge if the maximum demand goes up, and therefore a greatly increased lighting consumption may make it necessary to put up the fixed charge.

I have read the author's remarks on schools with great care; I am afraid that the load factor of a day school is fairly bad. In the elementary schools the children stay until 4.30 p.m., their Christmas holidays are short, and on several days in the year the maximum load must occur at the peak period. Another point is that the hours during which the children enjoy the additional lighting are few, and broadly speaking the school has to be equipped with an expensive lighting installation in order that the charwomen may have plenty of light when cleaning the building. If evening classes are held on the premises, however, the load comes on again at about 7 p.m. and obviously much greater use is made of the installation.

As regards the use of photo-electric cells for switching on artificial light when daylight becomes faint, we have tried and abandoned this type of equipment. On certain days the effect of clouds passing over the sun is sufficient to cut the cell in and out, with the result that the lighting is constantly changing. The eye itself has so much margin as between good light and bad light that one can afford to let the teacher switch on the artificial lighting when daylight has ceased to be adequate.

Mr. S. J. Patmore: I should like to refer to the psychological effect which two-part tariffs based on the maximum load installed produce on the consumer. I recently had the privilege of giving, on behalf of a supply authority, a lecture to a local Chamber of Commerce on the development of commercial lighting. The

subsequent discussion centred on the subject of two-part tariffs and after-hour lighting. The undertaking had a two-part tariff for commercial premises which was based on the wattage of the lamps installed; and, whilst it was proved conclusively in every case which was brought up that the owner of the shop would get his energy at a lower price on the two-part tariff, the fact of basing the fixed charge on the installed load seemed to be a psychological bar which kept consumers from going over from the ordinary lighting tariff to the two-part tariff.

Every supply undertaking ought to arrange a special tariff for all-night lighting. I do not agree with the suggestion that there should be different tariffs for different people, but I think that all commercial premises in a supply undertaking's area should be given a similar tariff if they keep their lighting on for extended periods.

Mr. Townley raised the question of the supply of lamps by supply undertakings to the assisted-wiring type of consumer. Will the day ever come when the supply authority, as part of its normal tariff, will supply all types of consumers with all their lamps and other current-consuming devices? There has recently been an example of a supply undertaking which seems to be giving away cookers. While the undertaking in question covers its costs by the tariffs it offers, the consumers are psychologically led to believe that they are obtaining their cookers free. In consequence, this undertaking has been able to develop considerably the domestic load in this field. Surely such tactics pay for consideration?

Mr. Townley says that he gives away lamps, and that by doing so he has increased the consumption of this type of consumer by 20%. I expect that if Mr. Townley did not do that, he, like many other engineers, would not get sufficient back from his assisted-wiring scheme to pay the interest and sinking-fund charges.

Dr. J. Adolph: I should like to make a remark about our tariff policy in Berlin. We have a fixed charge for domestic consumers, based upon the number of rooms, and a running charge of 20 Pfg. per kWh. If consumers go over to electric cooking we give them another rate; we reduce the running charge from 20 Pfg. to 8 Pfg. and impose a higher fixed charge. The reason is that, after changing over to electric cooking, consumers find that their supply for lighting is very cheap, because all the units which are used beyond the normal number are charged at 8 Pfg. I think that this system will lead to considerable development in the lighting of rooms.

Mr. W. M. Selvey: The standard of illumination now obtaining in the kind of building in which the author is more particularly interested will gradually be reflected in the desire of those who use that kind of illumination during part of their day's work to have equal illumination for their hours of leisure.

Very few people apart from those who are actively engaged in lighting buildings realize how bad some of the early fittings were from the point of view of giving reasonable and uniform illumination. I have met with a standard of lighting as low as 1 foot-candle under old-fashioned conditions, and have increased it to 4 foot-candles by using a larger number of points at smaller wattage, and suitable fittings.

In the early days I had the unusual experience of supplying a large batch of customers through current-limiters set at 150–180 watts, without metering. Supply was paid for at the rate of 1s. 6d. per week. It was essential in this case to provide the whole installation in the cheapest possible way. The estimates of consumption were based on the figure of 3 units per house per week, which was purely for lighting, although no objection was made to the use of an electric iron. The arrangement worked satisfactorily at first, but the consumption later crept up to 6 units per week, which is much the same as the author's figure. There were, however, complaints from the ordinary careful users as to the extravagant use of the supply by certain other consumers.

The undertaking being found in a prosperous condition, the arrangement was abandoned in favour of, I believe, a tariff of 1s. per week and 2d. per unit. By this time, however, the consumers had become so accustomed to a good standard of illumination that the consumption was not diminished by the change in the system of charging.

Dr. C. C. Paterson: The lighting industry has been in considerable danger on more than one occasion; the danger has always come at times when there has been an attempt to define the level of adequate lighting, to lay it down in codes, and to try to get it put into regulations. It is fortunate that the industry has managed to prevent that being done, because the standards of lighting which people would have called adequate 20–25 years ago, when there was a great move to define a standard, are very different from those which we consider adequate now. In these days, when there is much greater regulation of nearly everything, we have to be careful that such standards do not get laid down or obtain currency. I am sure that in 10 years' time our levels of lighting will be a great deal higher than those prevailing to-day. Daylight is about 50 times more intense than the artificial lighting to which we are accustomed, and there is no reason why artificial lighting should always be of a lower intensity than daylight. All that we have to learn is how to distribute the light from our sources in such a way that the enhanced light intensities are beneficial and not annoying. For instance, we must ensure that there are not great variations in illumination as between one portion of a building and another. It is noteworthy that in places where efficient street lighting has been installed there has been an improvement in domestic lighting and also in the lighting of public buildings, because of the contrast which people feel when they come from a brilliantly-lighted street into a poorly-lit building.

In the Ministry of Transport's recent report on street lighting the urge to lay down standards has been largely avoided so far as the level of lighting is concerned. Nevertheless, there are still those who would say that such and such an amount of lighting is the minimum to be permitted for streets. The moment such a minimum is fixed it tends to become the established figure. It is satisfactory to find, therefore, that in the Ministry's report this figure, which could have been put down as a minimum for street lighting, is expressed in terms of a wide range of sources from which people can choose.

Mr. R. Borlase Matthews (*communicated*): Table 2, dealing with commercial lighting, might be improved by the addition of a very large potential and existing lighting load, namely that to farms, of which there are 395 000. Of these, about 30 000 are already wired, and over 5 000 more are being wired each year.

I should like to refer to the importance of small consumers in rural areas. The Mid-Lincolnshire scheme, which I inaugurated, covers an area of 1 636 square miles in which no towns are supplied with the exception of the summer resort of Skegness. There are now over 20 000 consumers, with a consumption of 32 million units per annum, although the population density is only 108 per square mile. Nearly 2 000 cookers have been installed. This scheme was started to demonstrate the profitableness of a supply to a rural area unsubsidized by nearby large towns. Good dividends are being obtained, while the cost of energy to the consumer is less than that prevailing in many towns.

The tests described on page 299, in which 50 000 people chose how much electric light they would like to have for reading, give an exaggerated result owing to the period of the test being so short that the eye had insufficient time in which to adjust itself. I myself tried the test several times, and found that what was a satisfactory result with the short test was far too trying for comfort over a longer period. Nevertheless, there is no doubt that the carrying-out of these tests has made a large number of people realize that their lighting could be considerably improved to advantage, and has consequently increased lamp sales.

The introduction of the I.E.C. 100-watt study table-lamp has done a great deal to improve home lighting standards, both in this country and America. In the U.S.A. nearly 4 million of these lamps have been sold, and in consequence floor and wall lamps are being designed along similar lines.

Reference is made in the paper to home-lighting advisers, and in this connection it may be mentioned that the Brooklyn Edison Co. have staged a short play illustrating the work of one of these advisers. This is a very effective means of reaching an even larger number of people than is possible by actual visits to their homes, and also provides the names and addresses of those persons who become interested.

Mr. T. Stevens (*communicated*): On page 290 the author refutes the statement, made by some engineers, that the energy consumption of those not supplied with electricity would not justify the capital expenditure necessary to connect them to the mains; and I want to stress the fact that many supply authorities fail to give reasonable service.

On page 297 the author suggests that the adoption of the two-part tariff must show an advantage to existing lighting consumers. In this connection I would draw his attention to my contribution a short time ago to the Swansea discussion on Prof. Miles Walker's paper (see pages 585 and 586 of Vol. 80 of the *Journal*), where I showed that no benefit could accrue to many small lighting consumers unless they materially increased their use of electricity.

On page 295 the author refers to 70 000 licensed premises in this country, whilst in Table 2 the figure is 55 000 public houses. Do these figures refer to the same or to different premises?

On the same page he says: "By all means have a simple uniform tariff for domestic consumers." Many supply undertakings in Canada have only one domestic tariff, but in my opinion the author's suggestion of a uniform tariff is not practicable in Great Britain at the present time. It would, however, be practicable to have, say, three alternative tariffs, as follows: (*a*) A flat rate, which should be made uniform; (*b*) a two-part tariff, which needs reduction and standardization; (*c*) a tariff which the housewife can understand and from which she can deduce how much she will have to pay for any definite consumption. Such tariffs as are suggested under (*c*) are already in use in many parts of Great Britain.

Finally, on page 291, where the author refers to the "average demand per domestic consumer" he appears to mean the "maximum demand per average consumer."

[The author's reply to this discussion will be found on page 304].

EAST MIDLAND SUB-CENTRE, AT DERBY, 1ST MARCH, 1938

Mr. J. P. Tucker: Now that two-part tariffs are so popular one misses the multiplicity of metering which, with all its faults, did at least provide definite and useful information relative to the divergent uses of electricity.

Two-part tariffs are not confined to domestic use: they are now being applied to retail shops and also to industrial lighting. In spite of the decrease of accurate statistics due to these tariffs, there is much evidence to show that the lighting load accounts for a substantial percentage of the electricity consumed, and that lighting, both as regards size and number of lamps and also as regards hours of use, is still on the up grade. The author claims that in many areas the present lighting development is due more to national propaganda than to local development. I suggest that the most potent factor in the increased use of electricity for lighting is the reduced rate at which energy for lighting is now available.

In regard to the statement (page 290) as to the incorrectness of the opinion that small lighting consumers would not justify the capital expenditure necessary to get them, I would point out that so far as the supply engineer of to-day is concerned there is no such thing as a "small lighting" consumer. All property is regarded as a potential prospect for the various uses of electricity, including lighting, and it is this new outlook that justifies capital expenditure on mains which was at one time considered unprofitable.

Table 3 in the paper seems to me to be open to criticism in view of the very arbitrary process whereby it has been derived from Table 23 of the Electricity Commissioners' statistics for 1935–36.

Table 4 is also a surprise to me, and I should like to have particulars of the types of houses included in the groups. The 1936 lighting consumption for the Hendon

houses represents 7 060 lamp-hours (100-watt lamps) per house: surely this figure is much too high for the average house.

Again, in Table 6 I note a common factor which one must investigate with care; the annual lighting consumption represents in each case exactly 1 000 hours' use at the individual-consumer lighting demand.

Information of the sort given in Table 7 needs much amplification: why is there so much difference between the drapers' use in Islington (1 550 units) and at Gloucester (62 323 units)? Any phenomenal instance of use should be segregated so as not to distort the average figures; or, alternatively, a special note should be added.

I agree with the author that the new high lumens-per-watt lamps will not adversely affect the lighting consumption even though the lumen output from the new light sources may be 5 times greater than from the tungsten lamp. Nevertheless, I suggest that measures should be taken to combat the prevalent argument for the installation of new industrial units, namely that the higher-priced lamps are justified by the reduction they produce in the electricity account.

I support the author's advocacy of lighting-development officers, but I should like to see some curves giving the practical results achieved by such officers. Is the standard of lighting in America, where home-lighting advisers are employed, better than that prevailing in England?

Finally, it would appear from Fig. 2 that lighting units which cost the consumer less than 1½d. per unit are being sold too cheaply; for a supply at this price is commercially practicable only when the load factor is in excess of 40 %, and the plotted points do not show—except in one instance—that an increased load factor will result in selling at less than 1½d. per unit.

Mr. B. C. Bayley: When planning industrial lighting systems I have met with considerable difficulty in obtaining even distribution, owing to obstructions such as sprinklers and other services; and where air-conditioning plant is in use the trunking is a very serious obstruction.

The paper mentions that a check on 50 000 people revealed that the average intensity desired for reading is some 20 times greater than is commonly used; and I should be glad to know what this figure is.

The average domestic consumer pays very little attention to lighting, especially to the question of diffusion. For reading and needlework it is essential to health to have an intensity of at least 10 foot-candles, and the light should be well diffused. If the public were educated on these lines a considerable increase in consumption would follow.

Mr. W. F. Furse: Does the author know of any two-part tariff which would enable offices to get a supply for lighting during off-peak periods at a reduced price? Such a tariff would encourage offices to use more artificial light in the daytime, and to employ higher-intensity or indirect lighting methods. It is clear from Table 5 that at the present time the cost of lighting commercial premises is higher than that of lighting domestic premises.

Mr. J. Messent: I should like to point out that when a room is heated electrically the lighting consumption costs nothing, because the power needed for heating is reduced by the amount of that used for lighting.

I support the contention that we could advantageously use much more light. I have recently been experimenting with a mercury lamp in a room of about 12 ft. × 12 ft. To make the colour satisfactory a large proportion of incandescent light must be added, with the result that the total power rating is 600 watts. The illumination is not excessive, and as the effect is excellent it will become permanent.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON AND DERBY

Mr. W. J. Jones (*in reply*): Mr. Townley is especially qualified to speak on the value of the small consumer, and I agree that every channel should be explored to make the "minimum bill" consumer more profitable. It should nevertheless be borne in mind that while it may cost £2 to supply this small lighting consumer with his first unit, he does provides this revenue year after year, and, furthermore, it is a revenue which can be increased from greater use of lighting alone.

Lighting is not alone in requiring a capital expenditure of this kind; some supply undertakings will provide an electric cooker free of charge. In such cases the supply authority expends £10 to supply the first cooking unit and, further, does not receive sufficient revenue from the cooker to cover this capital expenditure until several years have elapsed. In other words, the earned annual revenue from this cooker will not meet the capital expenditure for several years, whereas in the case of lighting, as Mr. Townley shows, the earned annual revenue is sufficient to meet the capital expenditure during the first year.

I agree that accessories, and wireless in particular, account for the higher consumption of domestic lighting consumers in certain areas. In Finchley it was possible to examine the trend of lighting consumption without the complications of wireless, and in this connection Table 4 in the paper has special significance. I am in complete accord with Mr. Townley in his latter remarks regarding shop lighting and public lighting.

I am grateful to both Mr. Cunnington and Mr. Forbes Jackson for giving further examples of lighting load which either has long-hours use per annum, or, alternatively, does not coincide with the peak. They also support my contention that supply authorities should employ lighting-development officers capable of giving sound service to the consumer.

I find myself generally in agreement with Dr. Paterson, and would emphasize the need to distribute light from artificial light sources in such a way that it is acceptable to the eye. A badly designed installation imposes an artificial limit on the amount of light which can be employed usefully.

I agree with Mr. Borlase Matthews that there are large potential lighting loads in rural areas, and on the whole I accept his criticism of the choice of 50 000 people of the amount of electric light they would like to have for

reading. The test reveals a general desire for a much higher level of illumination than obtains at present.

Mr. Stevens draws attention to the fact that many small lighting consumers would not benefit by a two-part tariff unless they materially increased their use of electricity. I agree with this statement, but suggest that a progressive development policy would show consumers the advantages of increased lighting, and in the majority of cases the increased consumption would be sufficient to justify accepting the alternative tariff.

The 70 000 licensed premises in this country, mentioned in Table 2, embrace the 55 000 public houses. The difference in the figure is accounted for by restaurants, hotels, etc.

I agree that it is impracticable to have an identical tariff for all domestic consumers, but it should be possible to arrive at a tariff with the same secondary charge, even though the standing charge varies from district to district. In my opinion, even the latter could be standardized to a great extent.

I am grateful to Mr. Tucker for his confirmation that the lighting load accounts for a substantial percentage of the electricity consumed, and that hours of use are extending. While accepting Mr. Tucker's contention that the lower cost of electricity is a potent factor, I would not, however, agree that it is the only one. Any product, no matter how cheap, requires selling, and in such a service as electricity this can best be done on an organized basis by development officers.

I agree that the lighting consumption for Hendon houses is well above the average, since the houses are somewhat on the large size, but, even so, the consumption is below normal compared with the remarkable consumption obtained in small houses in Sunderland, Blackburn, and Croydon.

I, too, was surprised to find that in a number of towns throughout the country the annual lighting consumption represents approximately 1 000 hours' use of the individual consumer lighting maximum demand.

I welcome Mr. Tucker's remark that the new electric discharge lamp should be employed to give a higher level of illumination and not as a means to justify reduced electricity consumption.

Mr. Bayley asks as to the prevalent illumination; in homes, offices, and shops it is seldom more than 5 foot-candles.

I am unable to give Mr. Furse details of a two-part tariff to benefit offices during off-peak periods. Office lighting usually has such a poor load factor that it does not justify special consideration. In blocks of offices, corridors, and basements using light for many hours per annum, a straightforward two-part tariff with a reasonable kVA charge and unit charge would prove equitable to undertaking and consumer alike.

RADIOLOGICAL AND ELECTRO-MEDICAL APPARATUS*

By ROBERT S. WHIPPLE, Member.

INTRODUCTION

During the period under review it may be stated that, whilst no new principles have been discovered, considerable progress has been made in the construction of electro-medical apparatus, particularly in respect of ease of control and safety in handling.

Radiology still represents the most important aspect of electro-medicine. It is difficult for a layman to appreciate how large a part radiology plays in the ordinary routine work of a hospital. Its magnitude may be judged from the knowledge that it has recently been estimated that about 42 million X-ray pictures are taken annually, and that 1 million of these are produced in ten of the large London hospitals.

The most important advance in diagnostic radiology is probably the cineradiograph. The idea of the projection in rapid succession of a series of X-ray photographs taken of a moving body is not novel, but the development of a practical apparatus is due to the recent work of Dr. Russell J. Reynolds. Such equipment may now be obtained commercially and there is every probability that in the near future cineradiology will play a large part in the diagnostic examination of patients in the larger hospitals.

A further development is the tomographic method of taking radiograms and this is dwelt upon in some detail, since, although it has only recently been introduced into medicine, it appears to have great possibilities in the diagnosis of lesions and cavities in the lung and in many other regions of the body.

The development of X-ray tubes working at voltages approximating to 1 million volts is calling for the exercise of great ingenuity and powers of design. The successful installation of a tube working continuously at 750 kV at St. Bartholomew's Hospital for therapy shows that this country is not lagging behind in the development of the high-power tube.

It is impossible to say what will be the effects on curative medicine of the discovery of artificial radio-activity. By the invention of the cyclotron, Prof. E. O. Lawrence has produced an apparatus by means of which many elements may be rendered radio-active by the bombardment of high-speed protons or deutrons.

PROTECTION OF X-RAY TUBES

In the review of 1934 it was stated that the manufacture of protected tubes, viz. tubes in which X-ray protection was incorporated in the tube itself and which were enclosed in an earthed metal envelope, "had been taken up by most tube manufacturers." It is now true to state that this is universal practice. The only exceptions are gas tubes made for demonstration and laboratory work.

The shock-proof tube was a great step forward, but this has been followed by many ingenious devices, evolved by all the well-known manufacturers, to avoid injury to the patients or medical staff and to the apparatus itself.

The idea underlying the majority of the devices has been the substitution of oil insulation for that of air, so that the rectifying valves are now immersed in oil, not infrequently in the same tank as the transformers, thus reducing the length of high-voltage connecting leads to a minimum.

The International General Electric Co.† has recently introduced a "Maximar 400" unit in which the 400-kV tube is also contained in the same tank as the complete high-voltage circuit. Although the outfit is heavy, the controls are simple and readily operated. The exterior of the complete outfit is at earth potential.

Considerable development has also taken place in the control panels for operating the tubes. An automatic time-switch is universally incorporated in the panel, and by means of light signals and interlocking switches the likelihood of an operator working an outfit incorrectly is reduced to a minimum. In this way the life of a tube in general use in a hospital has been greatly extended.

DEVELOPMENT IN TUBE DESIGN

Perhaps the most important development in tube design has been the perfecting of the high-current tube with the rotating anode.

In this type of tube the anode is a rotating disc, so that the energy of the cathode stream is distributed over a ring instead of being concentrated on a small fixed area. A very much greater input of power can be used, with corresponding increase in X-ray intensity; this can be done, moreover, without increasing the size of the focus, which remains fixed relatively to the fixed parts of the tube, so that the time of exposure can be reduced while the good definition due to a sharp focus is maintained.

Tubes of this type may be divided into two groups. In the first the anode consists of a disc mounted on the shaft of a small induction motor, the rotor of which revolves inside the evacuated tube, the field coils or stator being mounted externally to it. In the second the anode disc is rotated by a motor completely external to the tube.

Three tubes of the first group are commercially available. In the "Rotalix," made by Messrs. Philips, the anode consists of a heavy copper disc in which is mounted a tungsten ring on which the stream of electrons falls. The heat generated is dispersed by radiation from heavy fins which run between stationary cylindrical flanges fixed to the glass tube and protruding beyond it. These in turn are connected to a large cooling sphere of relatively large heat-dissipating capacity. In the "Pantix," made by Messrs. Siemens, and the "Coolidge rotating-anode tube,

* A review of progress during the last 4 years. For a review of the subject up to the commencement of 1934, see L. G. H. SARSFIELD, *Journal I.E.E.*, 1934, vol. 75, p. 33.

† Represented in Great Britain by the Victor X-ray Corporation.

dual focus," made by the International General Electric Co., the anode consists of a solid tungsten disc which is run at a much higher temperature, approximately 3 000° C., when high output exposures are obtained. The amount of heat radiated at this temperature is very great and is transferred to the glass envelope almost instantaneously. The "Pantix" is cooled by a current of air passed over the outside of the glass envelope by means of a small ventilating fan which forms an integral part of the mounting. The same result is obtained in a simpler manner in the American tube by immersing it in oil in a completely sealed casing. Thus the high-voltage clearances can be diminished and the size of the unit correspondingly reduced. The "Rotalix" and "Pantix" tubes are made in two sizes, for which the effective area of the beam is $1 \cdot 2$ mm^2 and 2 mm^2 respectively. The Coolidge tube referred to above has the great advantage that it consists of practically two tubes in one. This result is obtained by means of two filaments of different areas either of which can be used as desired. With the smaller focus (1 mm^2, 150 mA) extremely fine definition is obtained, whilst with the larger focus (2 mm^2) excellent definition is given, but with the increase in power, 500 mA, reduced exposure is available. Mention should be made of the small form of rotating-anode tube the "Ray-proof Rotalix," which, although not shock-proof, is capable of work that could not possibly be done with a fixed-anode tube.

Owing to carefully designed interlocking devices used in controlling the electrical circuits operating the rotating-anode tubes, they can be used as freely as the normal shock-proof tubes.* Mention was made in the 1934 review of the tube developed by A. Muller and R. Clay in the laboratories of the Royal Institution.† This tube falls in the second group, in that the anode disc is rotated by means of an external motor actuating a shaft passing through a stuffing box; this necessitates continuous exhaustion. The heat is removed by a water stream circulating in the anode disc. This tube, which is intended for crystal analysis, has gradually been perfected, so that it will now run continuously at 50 kW. Currents up to 2 amperes can be passed through it, its normal working current being 1 500 mA at 27 kV. Tests show that the X-ray output is linear to the input power up to 35 kV at constant current, and up to 2 000 mA at constant voltage. It is hoped that a full description of this tube will be published in the near future.

An important development, from the point of view of the general utility of X-rays to medicine and to industry, is the production of smaller units which are shock-proof and portable, and yet are capable of giving excellent photographs. In the "Centralix," the "Heliosphere," and the "Victor Model F," models have been constructed to meet these special requirements. In all of them the high-tension transformer surrounds the X-ray tube, the high-tension leads being only a few inches in length. The units are protected by metal cases which are connected to earth through the supporting stands, while the transformers and tubes are hermetically sealed in oil. This method of construction produces weather-proof and robust units which are remarkably small for the work obtained from them.

From the point of view of deep therapy, the progress made in the manufacture of continuously evacuated tubes is of the greatest importance.

Messrs. Metropolitan-Vickers have made several such tubes,* the largest being the one installed in the Moselle Sassoon High-Voltage X-ray Therapy Department of St. Bartholomew's Hospital.† This tube, which is the most powerful one in the British Empire, was presented, with the building to contain it, to the hospital by Mrs. Sassoon. The installation was designed to give a beam of X-rays of higher intensity, and of shorter mean wavelength, than any so far employed in Great Britain for the treatment of cancer. The unit consists of a continuously-evacuated steel tube 30 ft. long containing the filament and target. This is supported at each end by porcelain insulators and extends horizontally across the treatment room, from one generator room to the other. The portion within the treatment room, that is the central 12 ft., is surrounded by a protective sheath, consisting of a 6-in. layer of "close-packed" lead shot between two co-axial steel cylinders. The protection sheath, in its turn, is surrounded by a steel cylinder, which carries the filters, diaphragms, and applicators, for defining the X-ray beam. The portion of the X-ray tube within the treatment room is shock-proof and ray-proof. The generating equipment comprises two generators, one designed to give a positive potential of 600 kV and the other a negative potential, in respect to earth, of the same value. The supply for each generator is from the 400-volt a.c. mains and is stepped up by transformers to 150 kV. By means of a modified Greinacher circuit, embodying columns of continuously evacuated thermionic valves and oil-immersed condensers, a rectified current at a constant potential of 600 kV may be obtained. Thus by using both generators a constant potential difference of over 1 million volts may be applied to the terminals of the X-ray tube. Experience has shown that the tube will run almost indefinitely at a voltage of 750 kV, and it is at this voltage that it is now being operated for deep-therapy work, the current given being about 5 mA. This must be regarded as a preliminary to treatment at higher voltages. All the operations necessary for the treatment of the patient are carried out from a central control room. The tube itself weighs 10 tons, but by means of auxiliary motor gear it can be handled without difficulty.

In the 1934 review mention was made of the cascade Coolidge type of tube in operation at the Memorial Hospital in New York. Several of these tubes are now in use in the United States and have been giving satisfactory service.

The distinctive feature of the tubes is the acceleration of the electrons in four stages, each one quarter of the total voltage. Four glass cylinders are connected together by metal plates, which in turn are connected to internal metal cylinders. The metal plates are maintained at their individual potentials by connection to suitable points on a cascade type of high-voltage generator. In this way it is possible to distribute more uniformly the

* That over 27 000 photographs of the chest have been taken with a rotating-anode tube at one of the London hospitals, at the rate of about 30 cases per hour, and with a current of approximately 450 mA, shows that this form of tube, in the hands of a good operator, is capable of sustained hard service.

† The first and smaller model of this tube was described by R. Clay in 1934 (see *Proceedings of the Physical Society*, 1934, vol. 46, p. 703).

* T. E. Allibone: *Proceedings of the Royal Society of Medicine*, 1936, vol. 29, p. 439.

† T. E. Allibone: *Engineer*, 1937, vol. 163, p. 452.

potential gradient between the cathode and anode, and the maximum voltage between any pair of electrodes can be kept safely below values at which field currents might lead to puncture.

In a tube built for operation in air at 800 kV the four sections had voltages increasing by steps of 200 kV applied to them: a current of 30 mA can be maintained continuously through the tube.

The tube, which is hermetically sealed and therefore does not need continuous exhaustion, is 14 ft. long, but as several transformers, condensers, etc., are required, a large and expensive building has to be provided.

Dr. Coolidge and his collaborators have therefore concentrated on the development of a high-voltage unit operated in oil. The result has been remarkably successful. The X-ray tube is a permanently exhausted unit, and is built in five glass sections (see Fig. 1) in which there is

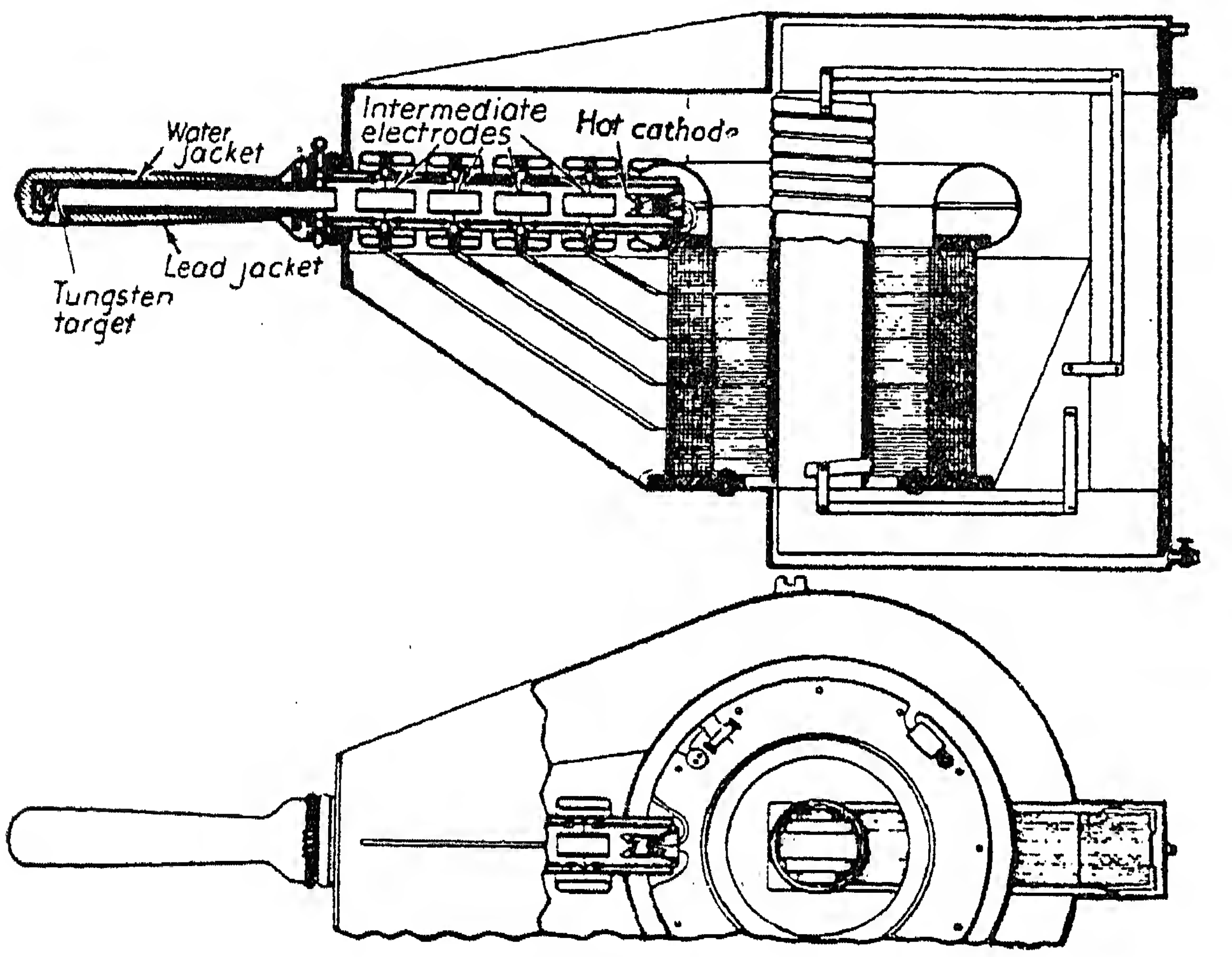

Fig. 1

a cathode, an anode, and four intermediate electrodes connected to the glass with Fernico* metal seals. The tube is constructed for use at 500 kV with the X-ray target, or anode, at earth potential. The intermediate electrodes in the form of hollow cylinders 2 in. diameter and 4 in. long, are spaced 1 in. apart and have a difference in potential between them of 100 kV. The tube has a total length of $50\frac{1}{2}$ in. and projects 22 in. beyond the transformer casing into which it is built. The projecting part is of nickel, 2 in. diameter; a water jacket, which is demountable, is fitted round it and a lead jacket also surrounds it.

The overall dimensions of the tank are: width 4 ft., height 4 ft., length 6 ft., which includes the projecting housing and the insulated part of the X-ray tube. A magnetic focusing coil is placed inside the lead sheath for adjusting the position and size of the focal spot.

The X-ray tube is connected direct to the transformer and rectifies its own current, the unwanted half-wave being suppressed. The large out-of-phase current taken by a transformer working under these conditions is minimized by providing the iron circuit with four gaps of predetermined width.

* This is a metallic alloy having a temperature coefficient of expansion exactly similar to glass and thus allows the metal to be of practically any desired thickness at the point of fusion to the glass.

When the tube is taking a normal load of 10 mA at 525 kV, the power in the primary circuit is 56 amperes at 185 volts; thus the power factor is approximately 0·7. It must be remarked that, from nearly every point of view, this unit shows a great advance. The authors state that " our experience with this equipment indicates that we can build other oil-immersed units for much higher voltages with this same general design, without increasing their volume and weight to excessive proportions or requiring the construction of special buildings in which to install them."*

Reference must be made to a new 1-million volt metalix X-ray tube recently introduced by Messrs. Philips. The tube, which is hermetically sealed and exhausted, is in three sections joined in cascade, each section being capable of withstanding a potential-drop of 400 kV; the total drop of over 1 million volts across the complete tube is divided up by connections to the junctions. The tube runs continuously with a current of 1 mA. The small length (6 ft.) is obtained by increasing the surface leakage path by double re-entrant glasswork. The electron emission is produced by a filament at one end of the

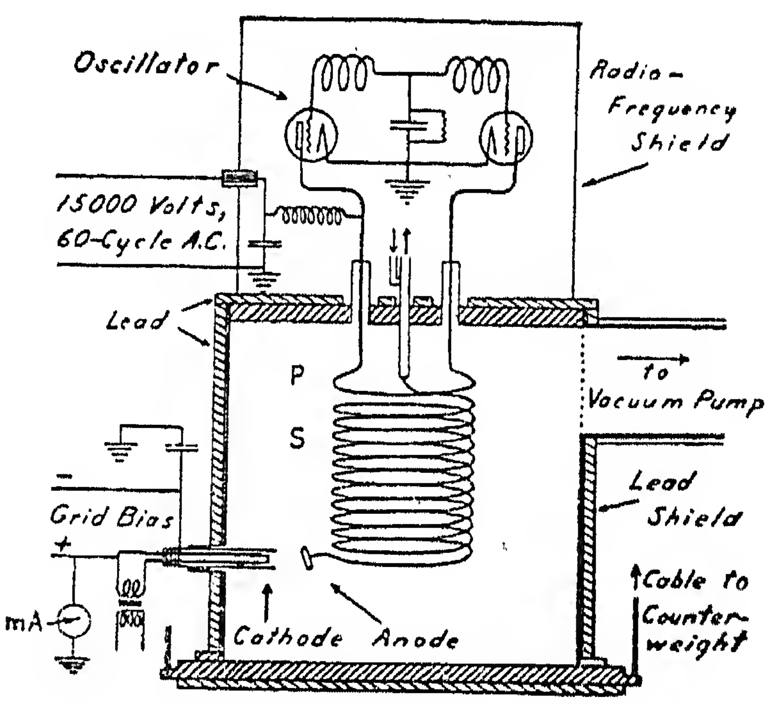

Fig. 2

tube, and the cathode stream is focused at the first of the two joints by a permanent-magnet device surrounding the discharge chamber. A deep-therapy X-ray department in which one of these tubes will be used is now being constructed in Amsterdam, but no details have been published of the electrical accessories, etc.

A novel high-tension generator and X-ray tube has been constructed by D. H. Sloan† at the University of California. Although originally designed as a positive ion accelerator it is now also being used for therapeutic work.

Such a tube and generator is installed at the Presbyterian Hospital, New York. Five patients can be treated simultaneously with it, although the number is usually limited to two or three. It is a development of the Tesla transformer (see Fig. 2), the high-tension generator consisting of a valve oscillator working at a frequency of about 5 Mc./sec., being coupled to a secondary winding made of concentric copper tubes and tuned to synchronism. The secondary winding carries at its high-tension end a tungsten disc which acts as the target, or anode, of the X-ray tube and is cooled by water flowing through the tubing. Both the primary and secondary windings of

* E. E. Charlton, G. Hotaling, W. F. Westendorp, and L. E. Dempster: *Radiology*, 1937, vol. 29, p. 329.
† *Physical Review*, 1935, vol. 47, p. 62.

the transformer are enclosed in a lead-shielded metal tank, about 4 ft. diameter, which is evacuated by means of oil-diffusion pumps. The anode voltage supply is unrectified 15 kV (r.m.s.), 60 cycles per sec. This greatly reduces the heat associated with a given maximum of generated voltage, and increases the maximum to which the output power can be modulated.

A hot filament contained in a tubular holder in the side of the tank acts as the cathode. A biasing voltage of 10 kV is applied to the filament to ensure that current only passes in one direction at, or near, the peak voltage of the supply. By running the filaments very hot, a push-pull pair of 300-kW valves can deliver about 1 000 kW at 6 Mc./sec. The X-rays are brought out through a window in the side of the tank containing the Tesla coil.

X-RAYS IN INDUSTRY

In industry the most important application of X-rays is still the examination of welds, joints, and castings. In America and on the Continent great progress has been made in the examination of the welds in boilers and high-pressure vessels. It has been stated that 75 miles of steel welds, running up to 3 in. thickness, have been X-rayed in the construction of the Boulder Dam in America. This immense piece of inspection involved the making of 159 000 separate X-ray exposures.*

Experiments on the examination of deep-seated cracks, or flaws, in metal castings by the tomographic method (see page **311**) are being made at the Research Department, Woolwich. Not improbably, this method of examination may prove useful in the testing of many materials used in industry.

In Britain the Air Ministry has made compulsory the X-ray examination of many parts used in the construction of aircraft. As other examples, amongst many, it may be mentioned that one large rubber manufacturer insists on the examination of the rubber soles made by his plant, the soles travelling on a conveyor belt between the X-ray tube and the fluorescent screen. For the sake of safety the observer looks at the image on the fluorescent screen in a mirror inclined at an angle of 45°. In some cases packed boxes of chocolates are examined by X-rays to see whether, by some mischance, a foreign body has been included in the sweets.

The value of X-ray crystal analysis in manufacturing processes has been more fully appreciated; in investigations, for example, on (*a*) strain release resulting from heat treatment, (*b*) the effect of rolling on crystal structure, (*c*) the effect on grain size caused by heat and mechanical treatment, etc., (*d*) the examination of plated surfaces, and in many other directions.

Thus the construction of portable, and transportable, X-ray plants for use in the works has become of much wider importance than that of studying welds, etc. In the 1934 review mention was made of a portable plant designed for use in the Research Department, Woolwich. Since then several firms have developed robust and portable outfits which are in daily use. An outfit, capable of both purely industrial and of scientific work in a factory, or research laboratory, has been placed upon the market by Adam Hilger, Ltd., under the name of "The Dexrae Industrial Unit." The whole outfit is made of metal (with the exception of one or two small parts), and robustness has been studied in every direction. The X-ray tube, which is of metal, is demountable, and has four anodes, or targets, made of different metals, so that different radiations can be employed. Thus an examination of a very wide range of metals and alloys can be made with the one tube. A Debye–Scherrer camera forms part of the outfit. The unit is mounted on rubber-tyred wheels and is completely self-contained, with the exception that it requires to be connected to an external a.c. supply.

Mention should be made of a mobile unit which, although made for the St. John and British Red Cross Society, could well be used for industrial purposes. With this apparatus, photographs can be taken with high-power X-ray tubes in the patient's home, or at the small hospital which is not equipped with an X-ray installation.* The apparatus is transported in a motor-car which is specially sprung for the purpose, and the power required to excite the tube is obtained from a generator driven by the car engine. The full output is 100 mA at 90 kV. The interior of the car is used as the dark room.

That radium is becoming a useful adjunct to the X-ray laboratory has been clearly shown from some experimental work carried out at the Research Department, Woolwich.† In a large casting, such as part of a gun mounting, it may be impossible to place an X-ray tube in the position necessary to examine a particular area in the casting. In such cases examination by radium, even for castings up to 10 in. thick, is most useful. Pullin points out that, in general, X-ray examination is preferable to radium, because of the better detail obtained with the X-rays. In cases where a structure varies considerably in thickness, and it is desired to show the variations in one picture, radium may well be employed. As a rule radium exposures are much longer than those required with X-rays, but radium has the advantage that it can be placed in position and left for many hours without attention.

A striking application of the usefulness of radium was shown when the radium was placed in the centre of a railway tyre, a photographic film being wrapped round the periphery of the wheel. Thus the whole circumference of the tyre was photographed in one exposure and a flaw in one place was clearly shown in the film. It may be stated that it is possible to use radium with almost the same precision as X-rays, and that in skilled hands it is proving a valuable adjunct to the radiographic laboratory.

It is only from a reference to the bibliography of the subject that the number of individuals working on radiological problems, and the great variety of those problems, can be realized. During the past four years the Physical Society has published "Reports on the Progress in Physics,"‡ and in these has been collected and summarized, with full bibliographies, the X-ray work, as distinct from the medical, of the past few years.

ARTIFICIAL RADIO-ACTIVITY

Development in the application of neutrons to biological problems is proceeding rapidly; in particular, their

* V. E. PULLIN: *Engineer*, 1935, vol. 159, p. 402.

* H. T. FERRIER: *British Journal of Radiology*, 1934, vol. 7, p. 426.

† V. E. PULLIN: Second Report of the Steel Castings Research Committee, Section 6, p. 101 (published by the Iron and Steel Institute, 1936).

‡ "Reports on Progress in Physics," 1934, vol. 1, p. 228; 1935, vol. 2, p. 301; 1936, vol. 3, p. 338; 1937, vol. 4, p. 332.

use in the production of radioactive isotopes of many of the elements by transmutation. Neutrons are produced when fast deutrons bombard the lighter elements, and can also be produced by allowing X-rays at over 1·8 million volts to fall on beryllium, so that for this work a source of very high voltage is a necessity.

The cyclotron of E. O. Lawrence and M. S. Livingstone* provides a stream of deutrons having an intensity of up to 100 μA and an energy of over 6 million electron volts. Electrostatic machines with moving belts are being built in America and in France, giving up to 2·5 million volts to earth, or, if two of opposite polarity are used, an overall voltage of 5 million volts.

A high-voltage generator due to R. G. Herb, D. B. Parkinson, and D. W. Kerst† merits description. It is of the belt type (due to Prof. Van de Graaf) and operates in a steel tank $5\frac{1}{2}$ ft. diameter and 20 ft. long under a pressure of 100 lb. per sq. in.‡ The generator is provided with a high-potential electrode of new design which serves both to give a high breakdown potential and to furnish a satisfactory potential distribution along the accelerating tube. The maximum potential of the generator is about 2 500 kV, and the highest steady potential at which reliable data have been obtained is 2 160 kV. An evacuated tube for the acceleration of ions has been developed which withstands the highest generator potential. The apparatus has been successfully used in experiments on atomic disintegration.

A somewhat similar machine has been installed at the Huntingdon Memorial Hospital, Boston, for working an X-ray tube at 1·2 million volts, 3 mA.

The cascade rectifier circuit has been developed in Eindhoven to give steady d.c. voltages up to 1·5 million to earth; while impulse generators working up to 3 million volts are in use, notably in Prof. F. Joliot's laboratory in Paris for the production of X-rays which are used to liberate neutrons from beryllium.

The possibilities of artificial radioactivity are far-reaching. As an example it may be mentioned that when common salt is bombarded it becomes radioactive, and it is most probable that radio-sodium when injected into the blood stream of a patient may have valuable therapeutic effects.

The comparatively few experiments that have been made on the biological action of neutrons show that, not improbably, they may play a large part in medicine in the near future. Dr. John Lawrence of the Yale Medical School, using the blood picture of a rat as an indicator, showed§ that the neutrons were about five times as biologically effective as X-rays per unit ionization in a sentinel ionization chamber; in some cases the relative biological activity is even greater.

CINERADIOLOGY

Almost immediately after the discovery of X-rays (in 1896) endeavours were made to obtain cinematograph pictures by their means. In 1897 Dr. John Macintyre, of Glasgow, showed a film 40 ft. long to illustrate the movements of a frog's hind leg. The film was obtained by taking a series of X-ray plate single exposures of the frog's leg in different positions, the pictures then being arranged in an order which showed the movement, the pictures being transferred to a cinematograph film for projection.

Several experimenters have since worked at the problem with many ingenious pieces of apparatus, some of them with considerable success.

Nearly all the pictures were taken by the direct method, viz. the one in which the object to be photographed is placed between the X-ray tube and the photographic film.

The indirect method, viz. the one in which a photograph is taken of the picture, or shadow, on a fluorescent screen, was adopted by Russell Reynolds in 1921. In 1925 he succeeded in producing a film showing the movements of the human heart. The important recent advance is in devising a method of obtaining a brilliant picture on the screen without exposing the patient to harmful doses of X-rays. This result has been obtained by means of a synchronizing mechanism which allows the rays to pass at the exact instant when the camera shutter is open and they are needed to produce a picture on the fluorescent screen. The details of construction of the apparatus have been fully described by Dr. Reynolds.*

There is no doubt that the diagnostic value of cinematographic records of a patient's condition taken at intervals during treatment will be of the greatest value. The apparatus has been placed as a complete unit on the market by Messrs. Watson and Sons (Electro-Medical), Ltd.

TOMOGRAPHY

Tomography, or planigraphy† as it is sometimes called in the United States, is perhaps the most important step made in medical radiology during the past four years.

In a radiograph of any part of the body the part close to the photographic film is always more clearly reproduced than the parts further away. For this reason one of the most difficult parts of the body to photograph is the lung, and the technique of a long-focus film distance has gradually been developed in order that the contrast between the more distant and the nearer parts of the lung should be reduced. The difficulties in lung radiography are largely due to the fact that the lung itself is translucent and that a considerable portion of a lung photograph is covered by shadows of the ribs. In a lung radiograph the shadows of numerous blood vessels, etc., are superimposed. Where this occurs contrasts arise, making interpretation difficult. Sometimes dense shadows of uniformly strewn seats of infection may cover the light area caused by a cavity, so that it cannot be discovered.

Bocage in 1922, and later other investigators, notably Ziedses des Plantes, evolved methods for the radiographic projection of plane sections of solid objects, but little use was made of the suggestions.

The first practical apparatus was designed by Dr. G. Grossman‡ (called by him a "tomograph") and was

* *Physical Review*, 1932, vol. 40, p. 19, and 1934, vol. 45, p. 608. A description of the cyclotron was given by J. D. Cockcroft in the Kelvin Lecture for 1936 (see *Journal I.E.E.*, 1936, vol. 79, p. 537).
† *Physical Review*, 1937, vol. 51, p. 584.
‡ The design and construction of enclosed high-voltage machines will in the future be influenced by the discovery of the insulating properties of CCl_2F_2, known commercially as "freon." The breakdown voltage of this gas is two or three times greater than that of air, and by using it under pressure it is possible to increase the breakdown voltage by a factor of 10.
§ *Proceedings of the National Academy of Science*, 1936, vol. 22, pp. 124 and 543.

* *Journal I.E.E.*, 1936, vol. 79, p. 389. A full bibliography dealing with the development of cineradiology is included in this paper.
† A useful summary of the subject is given by J. R. Andrews: *American Journal of Röntgenology and Radium Therapy*, 1936, vol. 36, p. 575.
‡ *British Journal of Radiology*, 1935, vol. 8, p. 733.

placed on the market by a German manufacturer. An English doctor, Dr. E. W. Twining,* has shown that the modern Potter–Bucky couch can easily be modified, by the addition of some comparatively simple mechanism, so that excellent tomographic pictures may be taken by means of apparatus fitted without difficulty to standard hospital couches.

The principle underlying the tomograph is simple and will be readily understood from the illustration (Fig. 3) provided by Messrs. Newton and Wright.

In the figure, 2 represents the approximate centre of the section of the body of the patient and is on the plane

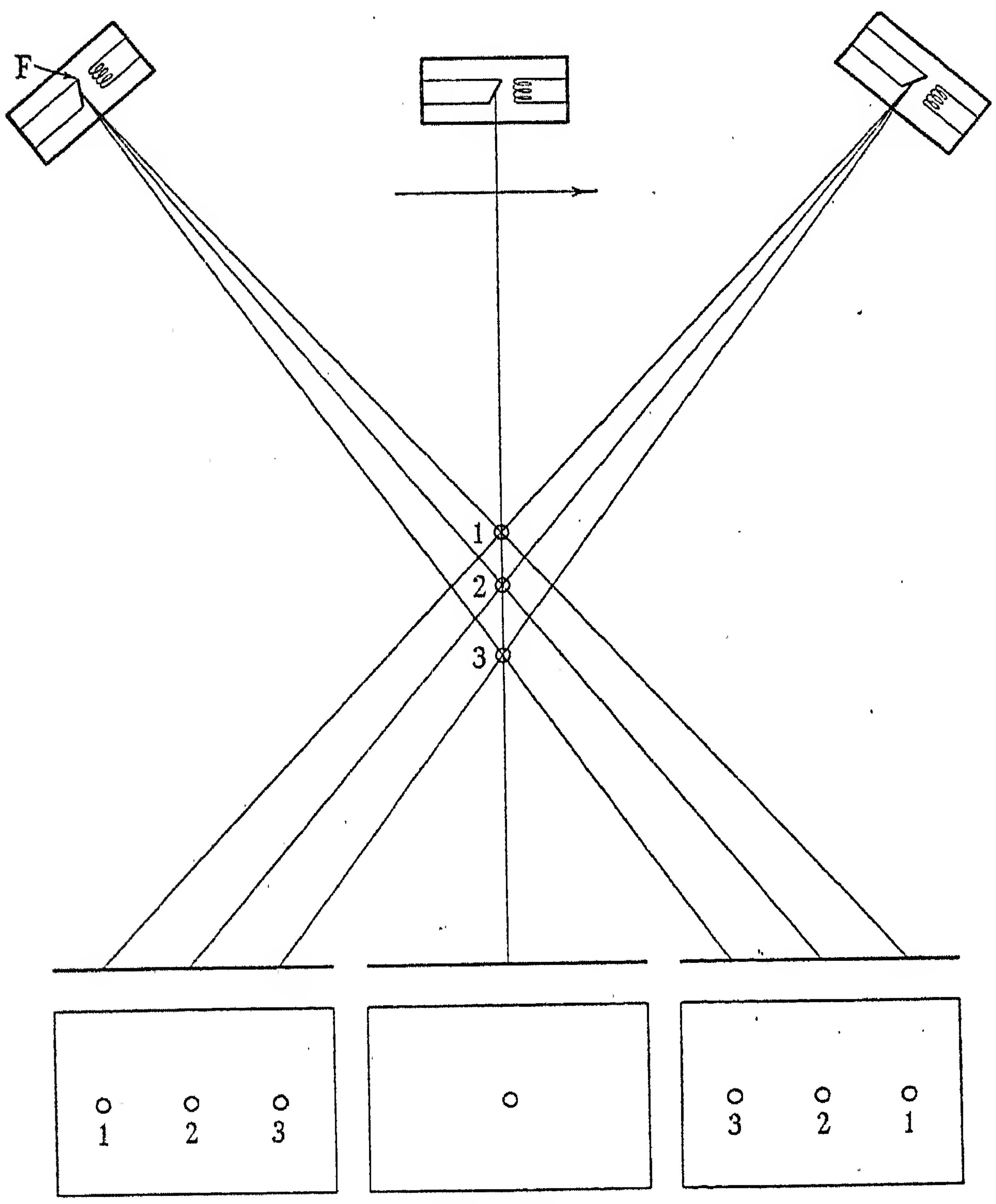

Fig. 3

of which it is desired to take a photograph. The focus of the X-ray tube is represented at F, and the film, shown by the dark line, is under the table on which the patient is resting. The method of taking the photograph is to move the tube by means of a rigid pendulum of linkage in the direction shown by the arrow, the photographic film being moved by the same mechanism at a determined proportional rate to that of the X-ray tube, but in the opposite direction. It will be seen, by the geometry of the arrangement, that the shadows of the parts on the plane 2 remain in focus during the movement of the plate from right to left of the figure, but that the shadows of all the objects that are not on the desired plane are blurred by the movement of the plate. By raising or lowering the position of the centre of rotation of the pendulum relative to the body of the patient, the plane of clear definition can be varied. In practice it is found that two or three photographs taken in planes about 1 in. apart will enable the position of a cavity to be determined. Pictures may be obtained with the patient in either a vertical or horizontal position, depending on the design of the apparatus used.

* *British Journal of Radiology*, 1937, vol. 10, p. 332.

In the case of the "Sectoscope," recently introduced by the Medical Supply Association, the patient, in a vertical position, and the film are rotated on vertical axes. One axis passes through the plane of the part of the body to be photographed and the other the plane of the film, both planes remaining parallel during exposure. This form of tomograph has the advantage that the X-ray tube is not an integral part of the apparatus and therefore any available tube may be used, and also that the tube is not moved during exposure.

The use of the tomograph is in its infancy, but the method is one of great diagnostic promise.

KYMOGRAPHY

Although the possibilities of cineradiology have hardly been explored, there is little doubt that the simple method of obtaining a photographic record of the movements of an organ by means of the kymograph has a considerable field of usefulness. A striking example is the obtaining of a record of a complete cardiac cycle in a few seconds. The kymographic method is not novel, but the developments in recent years are primarily due to Dr. Pleikart Stumpf of Munich. A full bibliography of the subject will be found in his paper dealing with X-ray kymography of the heart.*

The principle of the kymograph is simple. It consists of a form of Potter–Bucky screen in which a series of lead strips about 10 mm. wide and spaced about 0·4 mm. apart are mounted in a frame which is moved vertically downwards, by means of a simple mechanism, in front of the photographic film. In the case of the apparatus made by the Solus Electrical Co. the speed can be adjusted from approximately 2 to 6 seconds. An electric contact device operates the X-ray set, the mechanism being so designed that the grid starts and attains a uniform speed before the X-ray exposure is made. Thus a series of photographs are taken as the screen falls, parts of the film which have been exposed being continuously covered by the lead strips, and unexposed surfaces of film being correspondingly uncovered and exposed to the X-rays. In this way a record of the varying shape of the heart is reproduced and a series of changing contours shown on the film. Parts that do not move, for example the ribs, are shown as straight lines in the direction of movement of the grid.

APPLICATION OF X-RAYS IN ART

A development of X-ray technique which may prove of considerable importance in elucidating the methods of some of the old masters has recently been further advanced by Mr. F. I. G. Rawlins of the National Gallery. From historical evidence it had been gathered that some of the masters were in the habit of making a cartoon drawing of their figures in crayon, afterwards levelling it with oil or tempera, to the approximate level of the surrounds, which were painted with a heavy lead pigment. The X-ray examination confirms in a striking manner that this was the method adopted.

The examination is simple and instructive. The

* *British Journal of Radiology*, 1934, vol. 7, p. 707. Reference should also be made to a paper in the same journal by J. S. Hirsch which immediately follows that by Dr. Stumpf.

selected picture is mounted vertically on a suitably designed easel and a beam of soft X-rays (12·5 kV, 15 mA), working at a distance of 102 cm. from the focal point of the tube, is passed through the picture. In favourable cases the various layers of pigment are revealed and very minute differences in X-ray density are brought out.

Recent technique with the infra-red rays is also helping to elucidate problems connected with the deterioration of varnishes, etc., and the condition of pictures before cleaning is undertaken.

RADIOLOGICAL UNITS

At the Fifth International Congress of Radiology held at Chicago in September, 1937, the International Committee submitted revised recommendations with regard to X-ray and gamma-ray units. A new and generalized definition of the röntgen, which embraces both X-rays and gamma rays, was provisionally adopted until the next International Congress of Radiology, when it is hoped that almost every class of radiation may be included in a still more generalized definition.

It is stated that:—

(1) The International Unit *quantity* of *dose* of X-rays or gamma-rays shall be called the "röntgen" and shall be designated by the symbol *r*.

(2) The "röntgen" shall be the quantity of X- or gamma-radiation such that the associated corpuscular emission per 0·001293 gramme of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign. (Note 1 in the Appendix states that 0·001293 gramme is the mass of 1 cm^3 of dry atmospheric air at 0° C. and 76 cm. of mercury pressure.)

(3) Measurements of radiation quantity shall be expressed in "röntgens." Measurements of dosage rate shall be expressed in "röntgens" per minute.

Proposals were made as to the technique of measuring the radiations and of stating the intensity of the radiation received. The recommendations of the British X-ray and Radium Units Committee* were adopted almost in their entirety.

X-RAY AND RADIUM PROTECTION

At the same meeting the International X-ray and Radium Protection Commission submitted their recommendations, which were adopted by the Congress.

The Commission was impressed with the importance of increased and more thorough protection against stray radiations due to the increase in the voltages applied to X-ray tubes.

The Commission made a series of recommendations governing the protection of all those exposed to radiation, whether patients or medical staff.

A series of papers from workers from the Mayo Clinic have dealt with the dangers to the doctor of the examination of patients by X-rays, especially in the diagnosis by palpation of intestinal complaints. A recent paper by Drs. Stevenson and Leddy† emphasizes most strongly the care that should be taken by the doctor of his own hands when reducing fractures whilst at the same time he is observing the limb by X-rays.

It is pointed out that in the course of a single reduction of a fracture a doctor may receive serious injury to his fingers. The importance of speed in examination, short activation of the tube, and the keeping of the fingers outside the central beam of rays, is emphasized.

* *British Journal of Radiology*, 1937, vol. 10, p. 438.

† *American Journal of Röntgenology and Radium Therapy*, 1937, vol. 37, p. 70.

PHOTOGRAPHIC MATERIALS

It is gratifying to be able to report that, simultaneously with the development of the electrical side of X-ray apparatus, the manufacturers of photographic materials have not been idle: indeed, marked progress can be reported. The new sensitive films recently introduced by the Ilford and Agfa-Ansco companies under the names of "Ilfex" and "Agfa-Ansco" are a great advance with regard to definition, contrast, and speed. These films are used without intensifying screens, and therefore the definition obtained is a great advance on that given by the normal film with the intensifying screen, the improvement being most marked in the case of bone structure.

The use of more carefully constructed Potter–Bucky diaphragms, in which the thickness and spacing of the lead strips have been reduced to a minimum, has resulted in the more effective suppression of secondary radiation and an almost negligible weakening of the primary radiation. It is not improbable that in the near future, by employing high-intensity tubes, the modern Potter–Bucky diaphragm, and the new films mentioned, the use of the intensifying screen will disappear, even for the very short exposures required by modern technique.

New developers recently introduced by the Ilford and Kodak Companies, the "Blue Label" and the "D.19.b.," are improvements deserving of mention. In both cases the time of exposure has been reduced by approximately 40 % of that required a short time ago. The same two companies have also introduced developers by means of which films can be developed extremely rapidly. During some operations, e.g. the Smith–Petersen operation for fractures in the neck of the femur, it may be necessary to expose two or three films at short intervals and to develop them at once. In the case of these new developers the film can be fully developed, rinsed, and fixed, within 1–3 minutes.

A NEW PROTECTIVE ALLOY

J. C. McLennan and C. J. Smithells have described* a tungsten-nickel-copper alloy which, owing to its high density (16·5), is suitable for X-ray and radium protective purposes. The alloy, which consists of tungsten 90 %, copper 5 %, and nickel 5 %, can be readily machined, and is ductile and comparatively cheap. The absorption of filtered gamma-rays is approximately proportional to the density of the screening metal. The ratio of the absorption coefficient of the new alloy to that of lead is 1·37, which is very close to the ratio of the densities 1·32. A bomb for containing radium has been made from the material.

THE ELECTRO-CARDIOGRAPH

The last three years have seen the development of a new electro-cardiograph in which the place of the string

* *Journal of Scientific Instruments*, 1935, vol. 12, p. 159.

galvanometer or the loop oscillograph is taken by a cathode-ray oscillograph. The beam of the cathode-ray oscillograph, having no inertia, follows without difficulty the variations in electro-potential of the patient's heart. The movements of the cathode-ray beam are projected on to a fluorescent screen having a comparatively long after-glow, and are there photographed. The electrical energy available is small (rising to a maximum of about 2 mV) and must be amplified by means of valves to give measurable deflections on the oscillograph screen.

Dr. Douglas Robertson, in conjunction with Messrs. A. C. Cossor, has developed a portable form of electro-cardiograph. The instrument with its various electrical circuits has been fully described by Dr. Robertson, and reference should be made to his paper for further details.* Development work in connection with the portable string-galvanometer form of electro-cardiograph has also taken place. The three chief improvements may be summarized as follows: (*a*) The carrier holders supporting the quartz fibres or strings are interchangeable in the true sense of the word, so that a new fibre can be placed in position without difficulty, with the certainty that it will be in the centre of the optical field of view. (*b*) The fitting of a device to neutralize the patient's skin current. (This has greatly simplified the technique and has eliminated what was always a troublesome factor when taking an electro-cardiograph.) (*c*) A continuous-paper camera is now supplied and is interchangeable with the standard film camera. By its means records lasting for a comparatively long time can be taken.

The cathode-ray electro-cardiograph has recently, and rather unexpectedly, enabled a more detailed study of the currents of the heart to be made.

As is well known, electro-cardiography consists of the measurement of the electromotive forces liberated in the tissues surrounding the heart. Einthoven, the pioneer of this branch of electromedical technique, laid down the principles, which have been universally followed, governing the measurement of the voltage generated by the heart. He fixed three points on the body between which the voltages should be measured, viz. the right arm—left arm, right arm—left leg, and left arm—left leg.

Thus the complete human electro-cardiogram consisted of three records of the heart's voltage taken across the three corners of an equilateral triangle, in whose centre lies the heart. From these records the condition of the heart is diagnosed.

Recent workers have been impressed by this roundabout method of attack and, using the cathode-ray oscillograph (as an electro-cardiograph), have endeavoured to measure the actual voltage vector of the heart rather than its projection on the three sides of a triangle.†

This work has been illuminating, for not only has it shown that the voltage vector of the heart changes its magnitude during the beat but rotates, and that the direction of rotation depends upon whether the patient suffers from right or left hypertrophy.

To obtain these polar electro-cardiograms the cathode-ray oscillograph employed was fitted with three pairs of magnetic deflector coils set with their axes mutually at 120° and mounted on the neck of the tube. The amplified voltages from the three corners of the " Einthoven body-triangle " were taken to the three deflecting coils. Thus the excursion of the spot on the oscillograph screen from its zero position is an exact representation of the magnitude and direction of the voltage vector of the heart at any given instant.

By extinguishing the light spot periodically (by applying the voltage from a constant-frequency source to the modulator electrode of the oscillograph) the resultant picture appears as a curve composed of a series of long dots, and a cardiogram, i.e. a representation of the magnitude of heart voltage in respect of time, is produced.

The work has recently been carried further by taking simultaneous pictures on two tubes, the third lead of one of the tubes being connected to a fourth electrode on the right leg of the patient. In this way stereographic pictures of the direction and magnitude of the voltage vector of the heart have been obtained. These show that the vector not only rotates in the plane of the body face but moves backwards and forwards. This fact explains the difficulty of determining the point of application to the body of the fourth lead.

ULTRA-VIOLET RADIATION

Great advances have been made in the lamps used for producing ultra-violet radiation. The improvement consists primarily in the production of a new form of quartz mercury-vapour burner which generates radiation from the infra-red region down to the shortest wavelength which is transmitted through air, viz. about 1 850 Å.

As the quantity of liquid mercury in the burner is extremely minute, and the risk of mercury being spilt over the patient, if by some mischance the burner were to break, is negligible, the lamp can be placed horizontally over the patient. The lamps do not require tilting in order to be put into operation, and are thus self-starting. The burner is placed in a holder like an incandescent lamp, the holder being mounted in a metal reflector the back of which is arranged as a series of reflecting facets. The result in the case of the " Biosol " model recently introduced by Messrs. Philips* is to give an irradiated area of 16 in. by 32 in. at a distance of 20 in. This area is sufficient to cover the trunk of the human body, and is remarkably uniform in the intensity of the radiation received.

By means of a Uviol glass filter the radiation received from the lamp is practically limited to the region which is identical with the range of shortest wavelengths of the solar spectrum. Thus the filter should be used in the treatment of affections for which sunlight is required.

The Hanovia Co., who make a very similar lamp, have in their " Duo-therapy unit " produced an outfit which which will give either ultra-violet or infra-red radiation as required. The electrical circuits for operating these lamps are simple and efficient.

DIATHERMY

During the past three years a great deal of experience has been obtained both by medical men and manu-

* *Journal I.E.E.*, 1937, vol. 81, p. 497. A full bibliography is given in the paper

† R. BURGER: *Zeitschrift für Klinisch Medecin*, 1926, vol. 102, p. 603; F. SCHELLONG: *Kongressverhundlung für inn Med. München* (1936), 288; H. E. HOLLMAN and W. HOLLMAN: *Zeitschrift für Instrumentenkunde*, 1937, vol. 57, p. 147.

* A. VAN WIJK: *Philips Technical Review*, 1937, vol. 2, p. 18.

facturers in the use and development of diathermic apparatus. It is, nevertheless, true to say that no striking modifications or improvements have been made in the apparatus or technique.

There is still a divergence of medical opinion as to whether the ultra-short wavelengths (20 to 40 Mc./sec.) have any selective biological effects. An exhaustive study on the question has been made by Prof. W. E. Curtis and his colleagues, who state:* "Whilst the possible existence of specific actions of ultra-short waves cannot be denied, in our opinion such effects have not as yet been adequately demonstrated. We therefore find ourselves in agreement with the conclusion of a recent report to the Council on Physical Therapy of the American Medical Association, by Mortimer and Osborne: 'There is no conclusive evidence from the literature, nor were we able to substantiate the claim of specific biologic action of high-frequency currents (short-wave diathermy). In our opinion the burden of proof still lies on those who claim any biologic action of these currents other than heat.'"

* W. E. Curtis, F. Dickens, and S. F. Evans: *Nature*, 1936, vol. 138, p. 63.

DISCUSSION ON "GRID-CONTROLLED PHASE-ADVANCERS"*

Mr. Basil Wood (*communicated*): Although of considerable theoretical interest it is doubtful whether, owing to their apparent high cost, the rectifier phase-advancers described will find any commercial application. Rectifier phase-advancers would cost probably not less than £2 per kVA, excluding the transformer, as against £1 for static condensers and about the same for large synchronous condensers. The rating per unit would hardly exceed about 5 000 kW, which is the present limit for ordinary mercury-arc rectifiers. Very much larger ratings are required for voltage maintenance in large overhead networks, so that synchronous machines would still hold that field. The very rapid response which might be expected from regulating the kVAR of the rectifier condenser by grid control would be attractive, but the authors appear to imply in Section (5) that surges take place if the angle of lead is other than 90°. If this be so, the kVAR must be regarded as virtually fixed, so that the scheme has then no advantage over static condensers, which suffer from the defect that the kVAR delivered decreases as the square of the voltage. Incidentally, from the point of view of speed of response, a more practical application of the rectifier might be to the excitation of synchronous condensers, provided that the interturn insulation of the field windings could be made to stand up to the very high rate of change of excitation and excessive ripple which rectifiers would produce.

A partial application of the principle would be to the correction of the power factor of rectifiers or invertors. As described, the connections do not permit the phase-advancer to be employed alternatively or simultaneously for supplying a d.c. load. An arrangement described elsewhere by one of the authors† appears to overcome this disability, though still presumably subject to the surge trouble already referred to. A rectifier or invertor set consisting of two units in parallel connected to the same transformer, the one with natural retarded commutation and the other with equal artificial advanced commutation, would draw (or, in the case of an invertor, deliver) unity power factor, irrespective of the grid angle. The lagging current of the one would be compensated by the leading current of the other. There would be an internal circulation of wattless current between the two units, increasing with the grid angle. Unless a very considerable range of voltage variation is necessary, or inverted operation, it seems that such complication is not justified. The usual power factor of a 6-phase rectifier without grid control being of the order of 0·94 does not normally justify any expenditure on correction. This figure represents the product of displacement factor and distortion factor, of which only the former is improved by power-factor correction. The very considerable increase of harmonics at high grid angles, rather than the wattless current, may be a serious objection to employing grid control for wide voltage variation.

* Paper by Messrs. G. Babat and G. Rabkin (see vol. 82, page 429).

† *Elektrotechnische Zeitschrift*, 1937, vol. 58, p. 1400.

THE DIELECTRIC PROPERTIES OF CELLULOSE ACETATE*

By L. HARTSHORN, D.Sc., and E. RUSHTON, B.Sc.

[REPORT (Ref. L/T49) OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION]

(*Paper first received* 2*nd November*, 1937, *and in final form* 20*th January*, 1938.)

SUMMARY

The possibilities of cellulose acetate as a dielectric have received attention recently from several investigators, at home and abroad. This material has been under consideration by the Electrical Research Association for the past two years, not only from the point of view of its industrial applications, but as a medium for the investigation of fundamental phenomena.

The policy of the Electrical Research Association in regard to protracted researches of this nature is to release as much information as possible in the form of interim reports, rather than waiting until the final conclusions are available.

The report which follows is one of a series on dielectric phenomena which, for convenience, are related to materials or groups of materials widely used in industry. Other reports in this series relate to ebonite, paper, and varnished cloth.

The dielectric properties of cellulose acetate have been studied over the temperature range 25° C. to 90° C., using alternating voltages at frequencies covering the range 50 to 4 000 cycles per second, and also direct voltage. Preliminary tests showed that the power factor of commercial cellulose acetate may vary from 2 per cent to about 15 per cent. The detailed investigation was confined to samples of low power factor.

The material was found to absorb water from the atmosphere, and its power factor was reduced by drying. Samples which were dried at a temperature of 90° C. were regarded as completely dry, and such samples were used for most of the measurements. Other samples dried at 25° C. possessed a slightly higher power factor and therefore presumably contained traces of water. Measurements were made also on these samples in order to find out the effect of the water.

Measurements of permittivity and power factor were made by means of the Schering bridge fitted with a Wagner earth connection. Mercury electrodes were used.

It was found that as long as the voltage gradient does not exceed 3 kV/mm. (75 volts per mil), the permittivity and power factor are practically independent of the voltage, and the power dissipated is therefore proportional to the square of the voltage.

The power loss (W) was found to increase with increasing frequency (f) according to the law

$$W = G_0 + Af^{\alpha}$$

where G_0, A, and α, are constants. The index α was greater than unity. This law may be derived from Hopkinson's equations for dielectric absorption.

Within the range of this investigation, the power dissipated on the application of a definite alternating voltage diminished with rise of temperature up to 90° C. Samples containing traces of moisture and tested at the lowest frequency (50 cycles), and a sample under very high-voltage gradients (17 kV/mm.), formed the only exception to this rule. The true dielectric constant of the material increases with rise of temperature, but the component of the permittivity due to absorption, like the power loss, diminishes with rise of temperature.

Measurements were made under direct-current conditions of the absorption current flowing on charge and discharge, and also of the final leakage current obtained after a very long charge. Both the final leakage current and the absorption current flowing after times of charge of 10 seconds or greater, were increased by a rise of temperature. Such absorption currents obeyed Hopkinson's superposition principle approximately, but they appear to have no very close connection with the currents flowing in the a.c. experiments. The alternating currents are probably determined almost entirely by the absorption currents flowing during the first thousandth of a second of the charge.

When the voltage gradient in the material is increased beyond 3 kV/mm., the power loss increases more rapidly than the square of the voltage, i.e. the power factor and the a.c. conductance increase. This increase may be very large, the normal (low voltage) power factor being trebled in one case at 17 kV/mm. Several samples of the material broke down under voltage gradients of 15–20 kV/mm., but there was no obvious connection between the breakdown and any of the measured properties of the samples. The permittivity was also increased by the application of high-voltage gradients.

No general formula has been found to represent the increase of a.c. conductance and permittivity with voltage gradient. The initial portion of the increase can be represented by the equations previously found for varnished cloth, viz.

$$G_S = G_0(1 + pX^{\gamma})$$
$$C_S = C_0(1 + qX^{\eta})$$

where G_S and C_S are the values of the a.c. conductance and capacitance respectively of a sample in which the voltage gradient is X, G_0 and C_0 are the corresponding low-voltage values, and p, q, γ, η are constants. When the voltage gradient exceeds 10 kV/mm. the subsequent rate of increase of G_S does not follow the same law in all cases. Sometimes the above equations hold over the whole range of voltage gradient, but frequently the rate of increase of G_S with voltage gradient diminishes. In the latter case over the range 10 to 18 kV/mm. the rate of increase of conductance or power loss with voltage gradient is inversely proportional to the value of the gradient, which suggests that there is a tendency for the conductance to approach a limiting value as the voltage gradient is further increased.

The final d.c. conductivity also increases very considerably with voltage gradient. This increase was linear over the whole range.

A general discussion of the whole of the results obtained with this material suggests that its dielectric properties are determined by the motion of positive and negative ions within it. The increase of conductance with voltage gradient is probably not due to ionization by collision, but may possibly be accounted for by the developments of Debye's theory of inter-ionic attraction. It has been shown that the electrostatic forces between the ions will account also for variations of conductance and permittivity with frequency, and the

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

theory may therefore be regarded as a possible explanation of our results on the variation of dielectric properties with frequency, but the theory of polar molecules and that of Murphy and Lowry will explain certain features of the results equally well. No simple mechanism will explain all the results observed, and it is considered that several processes producing effects of the same kind, but on different scales of frequency, are operating simultaneously.

The Director of the E.R.A. will be pleased to receive comments from those who may have occasion to use this report.

CONTENTS

(1) INTRODUCTION

General.

The dielectric properties of paper have been investigated under a wide variety of conditions (Ref. L/T47).* A similar investigation has now been made on cellulose acetate, which somewhat resembles paper in its chemical composition but is entirely different in its mechanical properties, paper being fibrous and cellulose acetate homogeneous, or, at least, sufficiently so to be transparent.

Materials: Variations in Quality.

Several kinds of material were supplied by the E.R.A. The first material, L 617, was found to be so much inferior in electrical properties to cellulose acetate previously met with by the investigators, that it was considered that comprehensive tests on so unrepresentative a material could serve no useful purpose. Table 1 shows the values of permittivity and power factor of this material and also two other materials (L 618 and L 619). Since these latter possessed more normal electrical properties, they were selected for the purposes of this investigation.

* *Journal I.E.E.*, 1935, vol. 77, p. 723.

It is not possible to define these materials with precision, but since samples having approximately the same electrical properties as these two materials were obtained from three different firms they may be taken as being fairly representative of ordinary commercial cellulose acetate for electrical purposes. It is known that one of these materials gave on analysis 2 acetic acid radicles per cellulose unit $C_6H_{10}O_5$, and it is probable that all the materials examined were somewhat heterogeneous mixtures of about this average composition, and containing not less than 10 per cent of plasticizer. Probably material L 617 contained a larger proportion of plasticizer than the others.

Table 1

Cellulose Acetate Materials—Tested Under Room Conditions, as Received

Material	Frequency, cycles per sec.	Thickness, cm.	Permittivity	Power factor
L 617	1 000	$0\cdot038_5$	7·4	0·129
L 617	1 000	$0\cdot013_5$	7·0	0·108
L 618	1 000	$0\cdot012_8$	5·9	$0\cdot024_0$
L 619*	1 000	$0\cdot018_3$	4·3	$0\cdot029_6$
L 619	800	$0\cdot004_8$	4·8	$0\cdot035_9$

* This sample had been dried over strong sulphuric acid for several days.

Conditioning of the Samples.

It was decided that it would be more instructive to study the cellulose acetate in as dry a condition as possible, and thus to ensure that the results were representative of the material alone, and not of the material associated with moisture. The method of drying was essentially the same as that used for drying paper and described in Report Ref. L/T47. The sample was fitted into the electrode clamps with a guard ring, and placed in a constant-temperature enclosure. The temperature at which drying was carried out was usually 90° C. By means of the apparatus shown in Fig. 1 of Report Ref. L/T47, dry air was passed slowly over the sample until all the moisture had been driven off. This was indicated by measurements of the permittivity and power factor, which decreased steadily for some time and then became constant after 4–5 hours' drying. Mercury was then immediately applied to the sample by means of a two-way stop-cock, so that, during the process of drying and testing, the sample was not touched in any way. After the drying process had been completed, the mercury was always kept in contact with the specimen, so that when the temperature was lowered absorption of moisture was prevented by the presence of the mercury. In the case of paper it was found that moisture was absorbed* when the temperature was reduced even with mercury in contact with the sample, but this did

* In paper the process is probably one of adsorption rather than absorption, i.e. the water molecules are to be regarded as adhering to the surfaces of the fibres and not as permeating the material composing them. In cellulose acetate ordinary absorption is the more probable process.

not occur with cellulose acetate, as was evident from the reproducibility of the results obtained during successive heating and cooling of the material.

From Fig. 2 it will be seen that drying at 90° C. reduces the permittivity values of the sample by about 8 per cent or 10 per cent at all temperatures. The power factor is reduced by about 8 per cent at 25° C. and by about 4 per cent at 60° C. At 90° C. the effect of drying at the high temperature is more striking; the power factor is reduced from 0·0637 to 0·0096 at 50 cycles per sec., from 0·0439 to 0·0091 at 90 cycles per sec., from 0·0207 to 0·0095 at 300 cycles per sec., and so on until the values are nearly the same at frequencies of 3 000 and 4 000 cycles per sec.

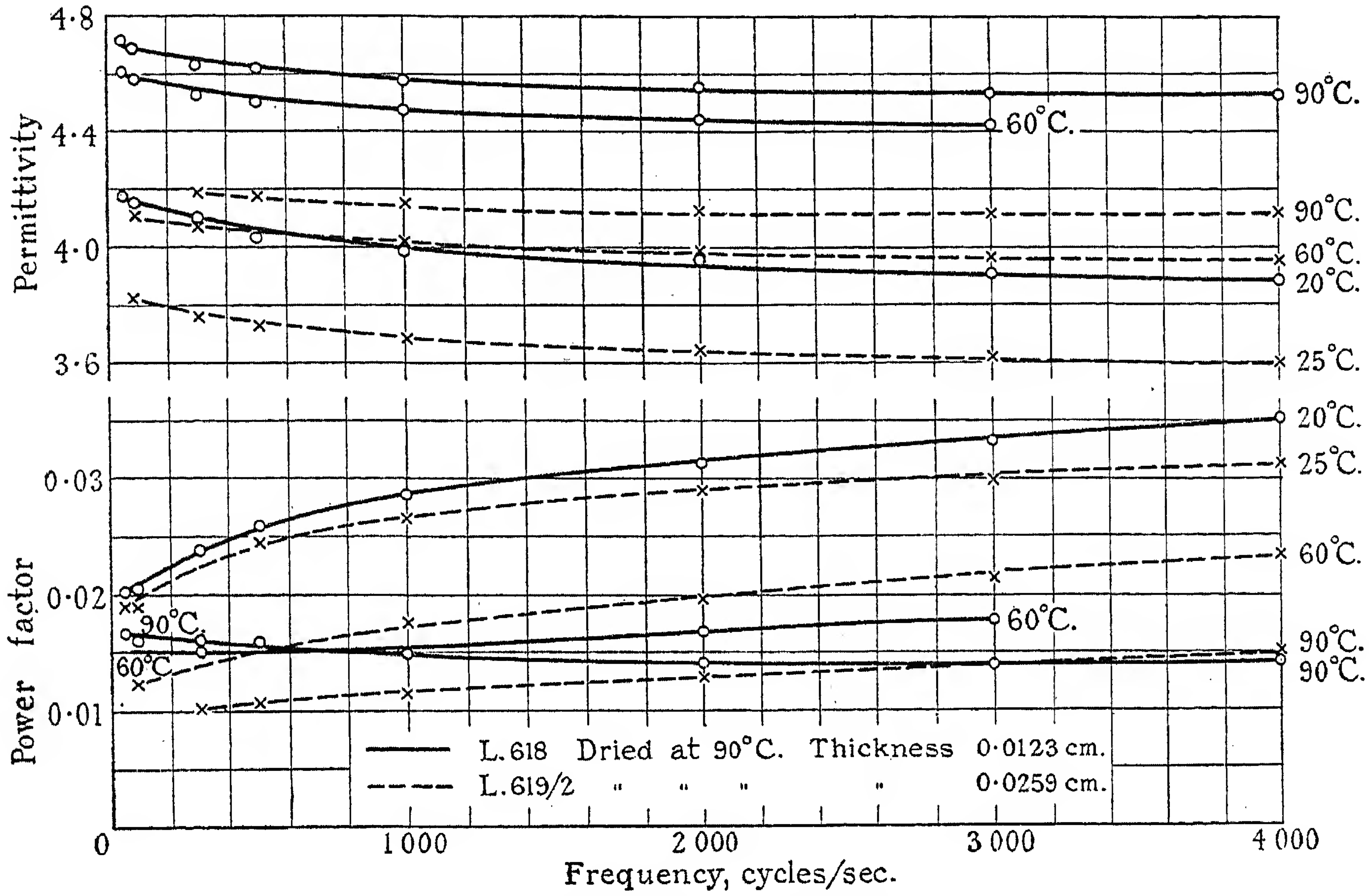

Fig. 1.—Variation of permittivity and power factor of cellulose acetate with frequency and temperature.

In one case the effects of drying at low and high temperatures were compared. The sample was first dried by passing over it air from drying bottles at 25° C. Then with the mercury always in contact with the specimen the permittivity and power factor were measured at temperatures up to 90° C. The mercury was then withdrawn, the sample dried at 90° C., the mercury replaced, and measurements again made at temperatures from 90° C. to 25° C.

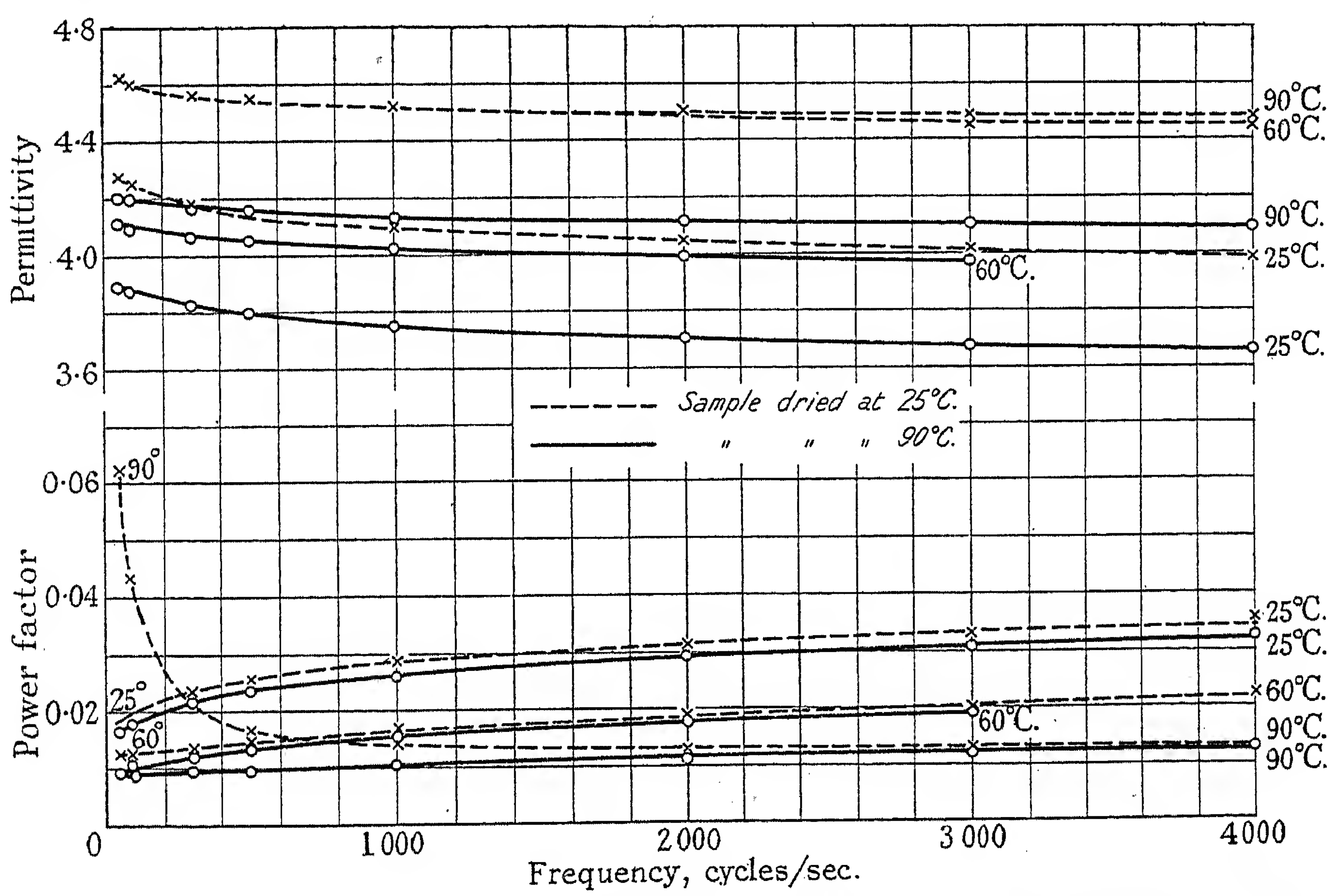

Fig. 2.—Effect of drying on the permittivity and power factor of cellulose acetate (Sample L 619/1, thickness 0·0183 cm.).

It is important therefore when testing this material

in a "dry" condition that the drying process should be carried out at high temperatures and not at low temperatures.

(2) LOW-VOLTAGE A.C. MEASUREMENTS

Method of Measurement.

The variation of permittivity and power factor of the samples at frequencies ranging from 50 to 4 000 cycles per sec. and temperatures from 20° C. to 90° C. was investigated. The sample was mounted in electrode clamps fitted with a guard ring and placed in a constant-temperature enclosure. The method of measurement was essentially the same as that used for paper. Mercury electrodes were used, and the measurements of capacitance and power factor were made by means of the Schering bridge, using a variable air condenser as the standard. All the components and leads were shielded, a Wagner earth connection was used, and the measurements were made by the substitution method.

It was found that at voltage gradients up to about 3 kV/mm. the permittivity and power factor of cellulose acetate were independent of the voltage applied, and consequently in this part of the investigation the voltage gradients used were kept below this critical value, thereby eliminating for the time being this particular variable. The voltage gradient actually used was of the order 1 kV/mm.

Permittivity, Power Factor, and Power Loss, as a Function of Frequency: Hopkinson's Equations.

In the authors' previous investigations of the dielectric properties of varnished cloth and paper, the variation of the properties with frequency was found to give important information as to the nature of the processes involved. In particular the behaviour of varnished cloth was found to be represented by Hopkinson's equations over a wide range of conditions. Other observers have found these equations to apply to observations on glass, mica, etc., whereas the present authors' own observations on paper would only fit them in a very few cases. It was therefore a matter of immediate importance to find out to what extent the same equations could be applied to cellulose acetate.

Hopkinson* (and later, Schweidler)† gave the following equations for dielectric "after-effect" or "absorption."

(1) For the absorption current i produced by a constant applied voltage V

$$i = V\beta C_0 t^{-\alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where β and α are constants of the material, C_0 is the instantaneous or geometrical capacitance of the sample, and t represents time measured from the instant at which the voltage is applied.

(2) For the power loss W due to an applied voltage V of sine-wave form and frequency $\omega/(2\pi)$

$$W/V^2 = G = G_0 + A\omega^\alpha \quad . \quad . \quad . \quad (2)$$

(3) For the capacitance of the sample at the frequency $\omega/(2\pi)$

$$C = C_0 + B\omega^{\alpha-1} \quad . \quad . \quad . \quad . \quad (3)$$

* "Original Papers," vol. 2.
† *Annalen der Physik*, 1907, vol. 24, p. 717.

Equations (2) and (3) are obtained from (1) on the assumption that $0<\alpha<1$.

G is, of course, the effective conductance of the sample. In equation (2) it is expressed as the sum of two terms, the normal or d.c. conductance G_0, and a term $A\omega^\alpha$ representing the part due to dielectric absorption. Values of G were calculated from the bridge readings by the use of the equation

$$G = C\omega \tan \delta \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where C is the capacitance of the sample, and δ the loss angle, at the frequency $\omega/(2\pi) = f$. The effective conductivity σ of the material per cm. cube was calculated from G and the dimensions of the sample, thus:—

$$G = \sigma A/d \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where A is the area of the sample and d is its thickness,

or
$$\sigma = \frac{\kappa f \tan \delta}{1\cdot 8} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where κ is the permittivity of the sample.

Usually the voltage gradient employed was 1 kV/mm. or 10^4 volts/cm., so that the power loss per cm^3 was $10^8\sigma$ watts. The values of this quantity were calculated for each case, and the relation between $\sigma \times 10^8$ and frequency (f) at each temperature was plotted with logarithmic scales. The points plotted were found to lie on straight lines, from which it was evident that the relation may be expressed in the form:

$$\sigma = a'f^\alpha \quad . \quad . \quad . \quad . \quad . \quad (7)$$

which is a form of equation (2) when the normal conductance is zero. The only case where the points plotted do not lie on a straight line is for the material L 619 (dried at 25° C.) at a temperature of 90° C. Here the curve tends to curl upwards at the lower frequencies, due to the fact that the d.c. conductance is no longer negligible. The complete equation may be obtained from (2). Thus

$$\sigma = \sigma_0 + a'f^\alpha \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where σ_0 = d.c. conductivity. The curve was found to fit this equation.

Table 2 gives the values of α obtained. It will be seen that α is greater than unity, and that it is almost constant at all temperatures.

It has been mentioned that Hopkinson and Schweidler obtained equations (2) and (3) from (1) on the assumption that α was positive and less than unity. The authors have now shown that their results for the power loss obey an equation of the form of (2) but having an index α greater than unity. Further, when attempts were made to fit the capacitance results to an equation of the form of (3), this also was found to give a value for α greater than unity, and a value for C_0, the instantaneous or geometrical capacitance, greater than the observed capacitance values C. This is manifestly absurd, and it can only be concluded that equation (3) does not apply in the present case. There does not, however, appear to be any objection to equation (1) or (2) with an index α greater than unity. Equation (1) is empirical and is known to be an approximation valid only for a certain interval of

time. The values observed for α have usually been less than 1, but J. B. Whitehead* has recently obtained values of 1·11 and 1·06 for impregnated paper by observations of the absorption current obtained on charging and discharging a condenser. Hopkinson's equations in their most general form are

$$i = V\beta C_0 f(t) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$W/V^2 = G = G_0 + \omega\beta C_0\int_0^\infty f(x)\sin\omega x\,dx \quad . \quad . \quad (10)$$

$$C = C_0 + \beta C_0\int_0^\infty f(x)\cos\omega x\,dx \quad . \quad . \quad . \quad (11)$$

tion current which causes the power loss. Within the range of the measurements, the power loss to be ascribed to normal conduction is negligibly small for the material in a thoroughly dry condition, but the small quantity of moisture which is left when the drying operation is carried out at room temperature gives rise to appreciable conductance when the material is subsequently raised to a high temperature.

The Variation of Dielectric Properties with Temperature.

The changes of permittivity, power factor, and power loss with rise of temperature over the range 25° to 90° C.

Table 2

VALUES OF α IN THE EQUATION $\sigma = \sigma_0 + a'f^\alpha$ . . . (8)
WHERE σ = POWER LOSS PER $CM.^3$ AT A STRESS OF 1 VOLT/CM.

Sample	Thickness, cm.	Temperature, ° C.	α	a'
L 618 Dried at 90° C.	$0{\cdot}012_3$	20	1·13	$2{\cdot}6 \times 10^{-14}$
		35	1·15	$1{\cdot}9 \times 10^{-14}$
		48	1·15	$1{\cdot}6 \times 10^{-14}$
		60	1·07	$2{\cdot}4 \times 10^{-14}$
		70	0·97	$4{\cdot}6 \times 10^{-14}$
		80	0·94	$5{\cdot}7 \times 10^{-14}$
		90	0·94	$6{\cdot}2 \times 10^{-14}$
L 619 Dried at 25° C.	$0{\cdot}018_3$	25	1·12	$2{\cdot}8 \times 10^{-14}$
		40	1·17	$1{\cdot}7 \times 10^{-14}$
		60	1·16	$1{\cdot}4 \times 10^{-14}$
		90*	1·01	$2{\cdot}7 \times 10^{-14}$
L 619 Dried at 90° C.	$0{\cdot}018_3$	25	1·13	$2{\cdot}3 \times 10^{-14}$
		40	1·16	$1{\cdot}6 \times 10^{-14}$
		60	1·20	$0{\cdot}9 \times 10^{-14}$
		75	1·19	$0{\cdot}8 \times 10^{-14}$
		90	1·14	$0{\cdot}9 \times 10^{-14}$
L 619 Dried at 90° C.	$0{\cdot}025_9$	25	1·09	$2{\cdot}9 \times 10^{-14}$
		40	1·14	$1{\cdot}9 \times 10^{-14}$
		60	1·18	$1{\cdot}1 \times 10^{-14}$
		90	1·14	$1{\cdot}0 \times 10^{-14}$

* The law $\sigma = \sigma_0 + a'f^\alpha$ does not hold strictly in this case.

If now we write $f(t) = t^{-\alpha}$ where $\alpha > 1$, we find that the integral in (11) becomes infinite, but the integral in (10) remains finite so long as α is less than 2, and for this case we obtain equation (2), where

$$A = \beta C_0\Gamma(1-\alpha)\cos\frac{\alpha\pi}{2}$$

We may conclude that the observed results obey Hopkinson's equation so far as these can be expressed in finite terms, and that the power losses in dry cellulose acetate are of the nature of dielectric absorption. On account of the value of α being greater than unity, the capacitance equation cannot be determined, and it is therefore not possible to find the values of C_0 and β, but there is no doubt that the observed diminution of capacitance with increasing frequency is another effect of the absorp-

* *Journal of the Franklin Institute*, 1929, vol. 208, p. 453.

are shown in Figs. 1–3 for the various samples investigated. The most remarkable feature is shown clearly in Fig. 3: the power loss in general diminishes with rise of temperature up to 90° C. The only exceptions to this rule are the values for the lowest frequency. At 50 cycles the material thoroughly dried at 90° C. gave a practically constant power loss at all temperatures; the sample dried at 25° gave a power loss at 50 cycles which increased rapidly with rise of temperature, but even for this sample the power loss diminished with temperature at the higher frequencies. The conclusions to be drawn from this are that the dielectric absorption, which is responsible for the larger part of the power loss, diminishes with rise of temperature, but the normal conduction, which is only appreciable in samples containing moisture, increases rapidly with rise of temperature.

In the case of dried paper, the power factor and power loss were found to be greater at low temperatures than at high, but this was found to be largely due to the fact that moisture was absorbed at the lower temperatures. The possibility that the increase of the power loss with diminution of temperature in cellulose acetate is due to a similar action was considered, but since the results were reproducible on alternately heating and cooling the sample, either slowly or rapidly, the effect must be regarded as due to temperature alone, apart from any question of absorption or adsorption of water.

The material L 618 was found to soften at temperatures greater than 60° C., and this fact must be borne in mind

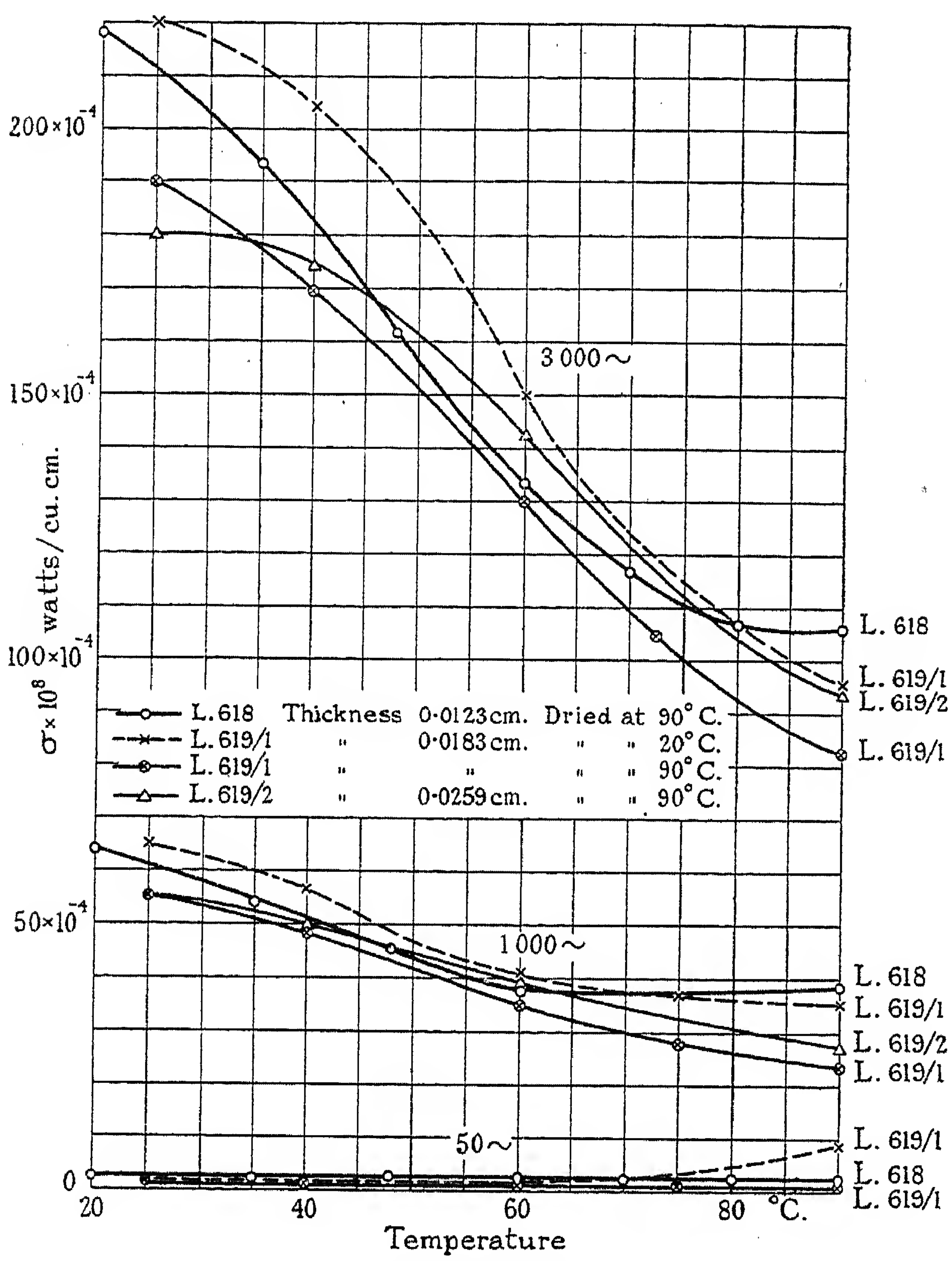

Fig. 3.—Relation between power loss and temperature in cellulose acetate.

when considering the results for this particular material. It will be observed that the power-factor results for this sample are rather irregular at temperatures of 70°–90° C., probably on account of changes occurring during softening, but it should be mentioned that measurements made at 20° C. before and after the observations at the high temperatures gave almost identical results, so that no permanent change occurs during the heating. No softening was observed during the measurements on material L 619.

It is a significant fact that when softening occurs there is no very large increase in the power loss due either to normal conduction or dielectric absorption. The change of slope of the curves for L 618 in Fig. 3 between 70° and 90° C. does perhaps represent a small increase of power loss due to softening, but the increase of normal conduction is certainly less than that due to the presence of a slight trace of water (cf. the two curves for L 619/1, Fig. 3, particularly at 50 cycles). One is tempted to conclude that conduction of an electrolytic character does not occur to any marked extent in this material in the absence of water. If any considerable number of mobile ions were present, their velocities would almost certainly be greatly increased by the softening and a rapid increase of conductance might be expected. This question will be considered in more detail later.

The changes of permittivity are also of interest. They are shown in Figs. 1 and 2, from which it may be seen that the permittivity invariably increases with rise of temperature. The temperature coefficient is about 0·2 per cent per deg. C. and is in general approximately constant over the range 20° to 90° C.

Now the permittivity may be regarded as consisting of two parts, the instantaneous value or true dielectric constant, and a term due to dielectric absorption. The values of power loss have shown that the absorption term diminishes with rise of temperature, and this is confirmed by the fact that the change of permittivity with frequency also diminishes as the temperature rises, as may be seen from Fig. 1. It therefore follows that the dielectric constant of this material must increase with rise of temperature. In this respect the material differs from many other materials such as paper and mica.

Comparison between Cellulose Acetate and Paper.

One of the objects of this investigation was to compare two such chemically similar and mechanically different materials as cellulose acetate and paper. The comparison is rendered difficult by the fact that the behaviour of paper is much less regular than that of cellulose acetate. There are considerable differences between samples of sulphate, cotton, and condenser tissue paper; it is difficult to prevent them from absorbing water at the lower temperatures, and some samples are subject to deterioration at the higher temperatures. However, from the evidence available (Ref. L/T47) the authors have concluded that oil-impregnation prevents the absorption of moisture, but does not produce any fundamental change in the dielectric properties of paper, and by comparing results for cellulose acetate and oil-impregnated paper certain general characteristics may be noted.

(*a*) In both materials the power loss is considered to be almost entirely due to dielectric absorption (in the absence of water), and this power loss diminishes with rise of temperature. In the case of paper the power-loss/temperature curve often reached a minimum value in the region 60°–90° C. This was not noted for cellulose acetate, but of course it may exist at a higher temperature.

(*b*) The power factor of dry cellulose acetate increased with increasing frequency. The curves for paper were less regular, but in the cases where the irregularities were least the results were essentially similar to those for cellulose acetate.

(*c*) The dielectric constant of cellulose acetate is of the order 4·0, and it has a positive temperature

coefficient of the order of 0·2 per cent per deg. C. The dielectric constant of dry paper varies from about 2·0 to 3·0, depending on the kind of paper, its density, etc. It is very nearly constant for all temperatures in the range 20° to 90° C., but there is some evidence for a small negative temperature coefficient for cotton paper and condenser tissue (not greater than 5×10^{-4} per deg. C.), and a positive temperature coefficient of about 1×10^{-3} per 1° C. for sulphate paper (Fig. 9, Ref. L/T47).

(*d*) Cellulose acetate, like paper, takes up a certain amount of water from the atmosphere, and in order to dry the material thoroughly it is necessary to raise its temperature to, say, 90° C. This action is, however, very much more marked with paper than with cellulose acetate. In both cases the absorption of water causes an increase in the power loss. In the case of paper the water absorption caused the power loss to increase with rise of temperature, but for cellulose acetate this only applied to the loss due to normal conduction; the loss due to dielectric absorption still diminished with rise of temperature.

Surveying the whole data, we conclude that the fundamental dielectric properties of dry paper and dry cellulose acetate are very similar, and that the phenomenon of dielectric absorption, which is the main cause of the power loss in these materials, probably does not depend on the fibrous structure of the paper, i.e. on the network of air spaces and fibres, but occurs in the interior of each fibre. When, however, the materials are in an atmosphere containing small traces of water vapour, their properties are not so similar, and it is probable therefore that the phenomena observed with paper in this condition are largely due to its fibrous structure, i.e. adsorption of water occurs at the surfaces of the fibres, and the enormous surface area available is to a large extent responsible for the differences between the properties observed in the two cases.

(3) LOW-VOLTAGE D.C. MEASUREMENTS

In order to compare the properties of the material under d.c. and a.c. conditions, measurements were made of the current flowing through a sample on the application of a constant voltage of 200 or 400 volts. Sample L 619, of thickness 0·0183 cm., was used. The voltage was obtained from a battery, and the current measured with an ordinary moving-coil galvanometer. The total movement of electricity in the sample, due to the application of the voltage, may be divided for convenience into three parts, the instantaneous or normal charge, the absorption charging current which gradually falls to zero, and finally a current of constant value, often called the normal leakage or conduction current. In order to avoid any assumptions as to the nature of the final constant current, it will here be called simply the final conduction current: the ratio of this current to the applied voltage will be called the final conductance. The difference between the observed current at any instant and the final current will be called the absorption current at that instant, and the ratio of this current to the applied voltage will be called the absorption conductance. The quantities measured were the absorption conductance as a function of time, beginning 10 seconds after the application of the voltage, and the final conductance. The discharging current obtained when the voltage was reduced to zero after a prolonged charge was also observed. The results are shown in Fig. 4 and Table 3.

Fig. 4 shows the absorption current plotted against time with logarithmic scales. It includes both charging and discharging currents, but it must be remembered

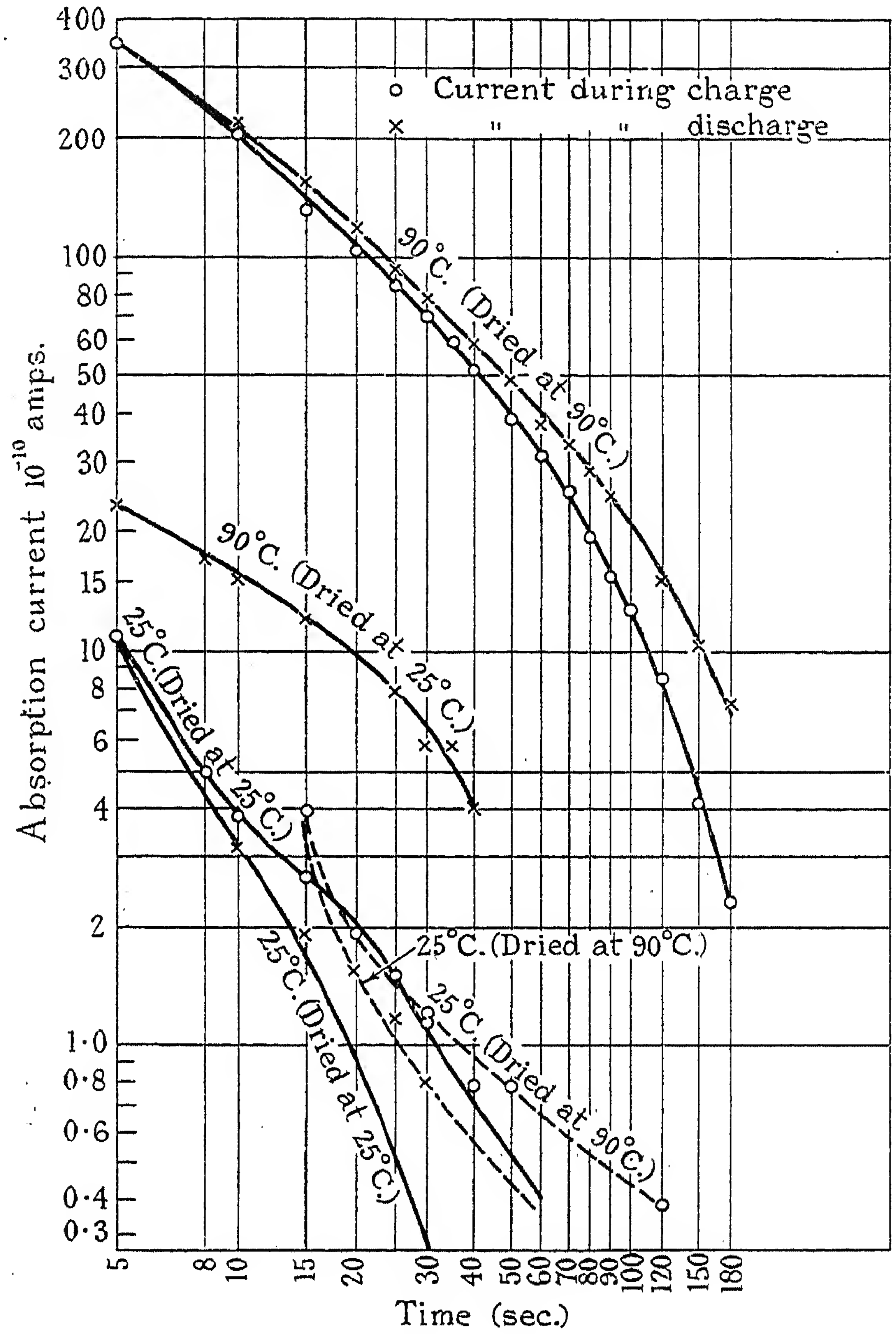

Fig. 4.—Absorption current with time.

that, in order to obtain the values for the charge, the final current has been subtracted from the total observed current. It is to be noted that the curves for charge and discharge are nearly, but not quite, the same, from which we may infer that the observed absorption conforms approximately to Hopkinson's superposition principle. It is difficult to say whether the discrepancy is greater than the experimental error or not. The smallest currents could not be measured with very high accuracy, and there is always the possibility of a slight change in the condition of the sample during the time required for a set of observations. However, the discrepancies do not appear to be of importance at this stage.

The next point to be observed is that the lines representing the results are not straight, so that equation (1) cannot be applied to the current flowing after a time

of charge of the order 10 to 100 seconds. Further, the slope of the curves—the index α of equation (1)—is in several cases less than unity. The value of α deduced from the a.c. observations is always greater than unity, so that the curve of the absorption current must curl upwards as t becomes smaller. A similar state of affairs was found for varnished cloth (Ref. L/T44).

When comparing the curves for material dried at 90° C. and at 25° C., it should be borne in mind that the material dried at 25° C. probably only differs from that dried at 90° C. in that it contains traces of water. At a temperature of 25° C. this water appears to have very little effect on the absorption current; at 90° C. it reduces the absorption current to about one-tenth of the value for the "dry" sample, but increases the final conductance to ten times its value for the dry sample (Table 3). The a.c. conductance at 50 cycles is always large compared with the final d.c. conductance, or the absorption conductance after 10 seconds. This absorption conductance, like the final conductance, is always increased by a rise of temperature even when the a.c. conductance is diminished. The inference is that the absorption current after 10 seconds has little connection with the a.c. conductance at frequencies greater than 50 cycles. The complete absorption curve covering both large and small time intervals must change its shape as the temperature rises, so that the curves for two different temperatures must cross one another. In this connection it is interesting to note that the shape of the observed portions of the absorption curves (Fig. 4) is changed by a rise of temperature, and to a smaller extent by the presence of a trace of water.

An interesting feature of the results for this material is the comparatively rapid decay of the absorption current. In all cases the current had become sensibly zero in less than 200 seconds, whereas the current in varnished cloth could be observed for over 10 000 seconds.

Table 3

VALUES OF ABSORPTION, FINAL, AND A.C. CONDUCTIVITY

Temperature, °C.	Drying temperature, °C.	Time from application of 200 volts, sec.	"Absorption conductivity," mho	Final conductivity, mho	A.C. conductivity (50 cycles), mho
25	25	10	$1\cdot9 \times 10^{-12}$	$1\cdot9 \times 10^{-12}$	10×10^{-9}
		100	$0\cdot0 \times 10^{-12}$		
90	25	10	10×10^{-12}	522×10^{-12}	36×10^{-9}
		100	1×10^{-12}		
25	90	15	$1\cdot9 \times 10^{-12}$	$0\cdot2 \times 10^{-12}$	8×10^{-9}
		100	$0\cdot2 \times 10^{-12}$		
90	90	10	102×10^{-12}	50×10^{-12}	5×10^{-9}
		100	6×10^{-12}		

(4) HIGH-VOLTAGE A.C. MEASUREMENTS

The Occurrence of Breakdown.

The authors' experiments on varnished cloth have shown that when the voltage gradient to which this material is subjected is increased beyond a certain point, the power factor of the material begins to increase, and continues to do so until breakdown occurs. A similar investigation of the properties of cellulose acetate under high voltage-gradients has now been made. The progress of the investigation was impeded to a considerable extent by the failure of several samples under voltage gradients of the order of 15 kV/mm. Inspection showed that the samples had become punctured in one or two places, sometimes between the high-tension electrode and the guard ring, and sometimes between the central portions of the electrodes. There was no blackening of the material at the punctures, which seemed to be simply due to local melting of the material. The breakdowns occurred without warning, i.e. no rapid increase of power factor was observed just before they occurred.

It is known that, under ordinary test conditions, cellulose acetate which has not been specially dried breaks down under a voltage gradient of the order of 40 kV/mm. It is, therefore, at first sight somewhat surprising that the samples, which had been carefully dried, should break down under a voltage gradient so much smaller. The experimental conditions were, however, considerably different from those of the ordinary breakdown test. The electrodes were larger (170 cm^2), they were of mercury, and the material had sometimes been under stress for some hours, although in the majority of cases breakdown occurred while the voltage was being raised to its maximum value, as a preliminary to the taking of readings.

The fact that the overall power factor of the sample did not increase very rapidly just before the breakdown, suggests that the breakdown is a highly localized phenomenon and that it occurs in minute portions of the material which are of relatively poor quality. The chances of the inclusion of such defective spots in the sample under test would be increased by the use of a large electrode, and this may account in part for the low breakdown voltage. The risk of failure in this manner would be lessened by the use of a sample of two layers. Such a sample was used successfully at temperatures of 25° and 50° C. under alternating voltage gradients up to 18 kV/mm., but later on it failed during the d.c. experiments with a voltage gradient of about this amount.

The Measurements.

The measurements were made by means of the Schering bridge, arranged for use with voltages up to

5 000 (Fig. 5). The sample C_1 was mounted in the mercury-electrode clamps, which were made to withstand voltages of several thousand. The standard condenser C_2 was specially constructed for these investigations. Both of its banks of plates were insulated by pillars of fused quartz from the case, which could, therefore, be connected to earth as shown in Fig. 5. The measurement of the capacitance and power factor of the sample for any value of the applied voltage was made in the usual way and calls for no special comment, but it will be obvious that when the simple earth connection of Fig. 5 was used, it was necessary to apply corrections for the capacitances to the guard ring of the sample, and the screen of the standard condenser, which shunted the resistances R_4 and R_3 respectively. Check measurements were made in one case with a Wagner earth connection. These gave the same results as the simpler connection shown.

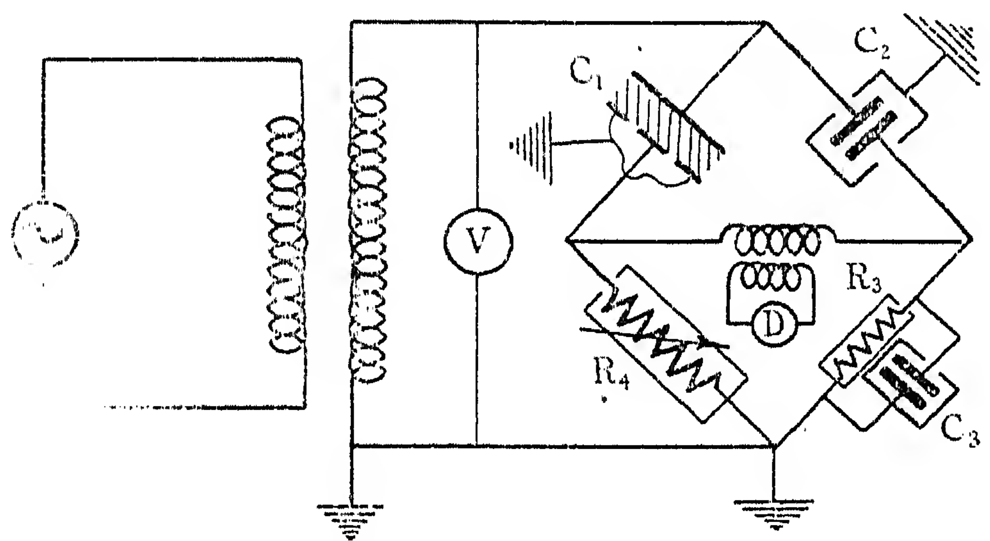

Fig. 5.—Schering bridge for use up to 5 000 volts.

A comparison of the results obtained with samples of different thickness was considered to be of importance. Measurements were therefore made on single sheets of thickness $0 \cdot 025_9$ cm., $0 \cdot 013_0$ cm., and $0 \cdot 004_8$ cm. The sample of thickness $0 \cdot 025_9$ cm. was dried at 90° C. before testing; the sample of thickness $0 \cdot 013_0$ cm. was tested first in an undried condition and then after drying at 90° C. The thinner material of $0 \cdot 004_8$ cm. thickness was tested in an undried condition.

A sample consisting of two sheets of total thickness $0 \cdot 014_5$ cm. was also tested after being dried at 90° C.

The temperatures at which measurements were made were 25° C., 50° C., and 70° C., and the frequencies chosen were 50, 800, and 1 000 cycles per second.

Hysteresis Effects.

As in the case of the investigation on varnished cloth, the applied voltage was increased to its maximum value and reduced to zero several times in succession before any measurements were made, so that the non-reproducible effect of the first application of the voltage was not included in most of the measurements. The permittivity and power factor were then measured with the lowest voltage that would give the required sensitivity, after which the applied voltage was gradually increased up to its maximum value, and then reduced to its original value, readings of permittivity and power factor being taken at suitable stages. The whole series of readings was taken as quickly as possible so as to avoid undesirable changes in the condition of the material.

In the case of the thicker samples, the readings at any given voltage gradient were the same for increasing and decreasing values except at the frequencies of 800 and 1 000 cycles per second, when the values of capacitance and power factor were slightly higher at the end of the tests than at the beginning. The sample of thickness $0 \cdot 004_8$ cm., however, showed much larger differences between the two sets of readings, the capacitance and power factor values being respectively about 1 to 4 per cent and 2 to 18 per cent higher for falling than for rising voltages. If, however, readings were taken an hour later, the capacitance and power-factor values were found to have decreased, and a day later they were

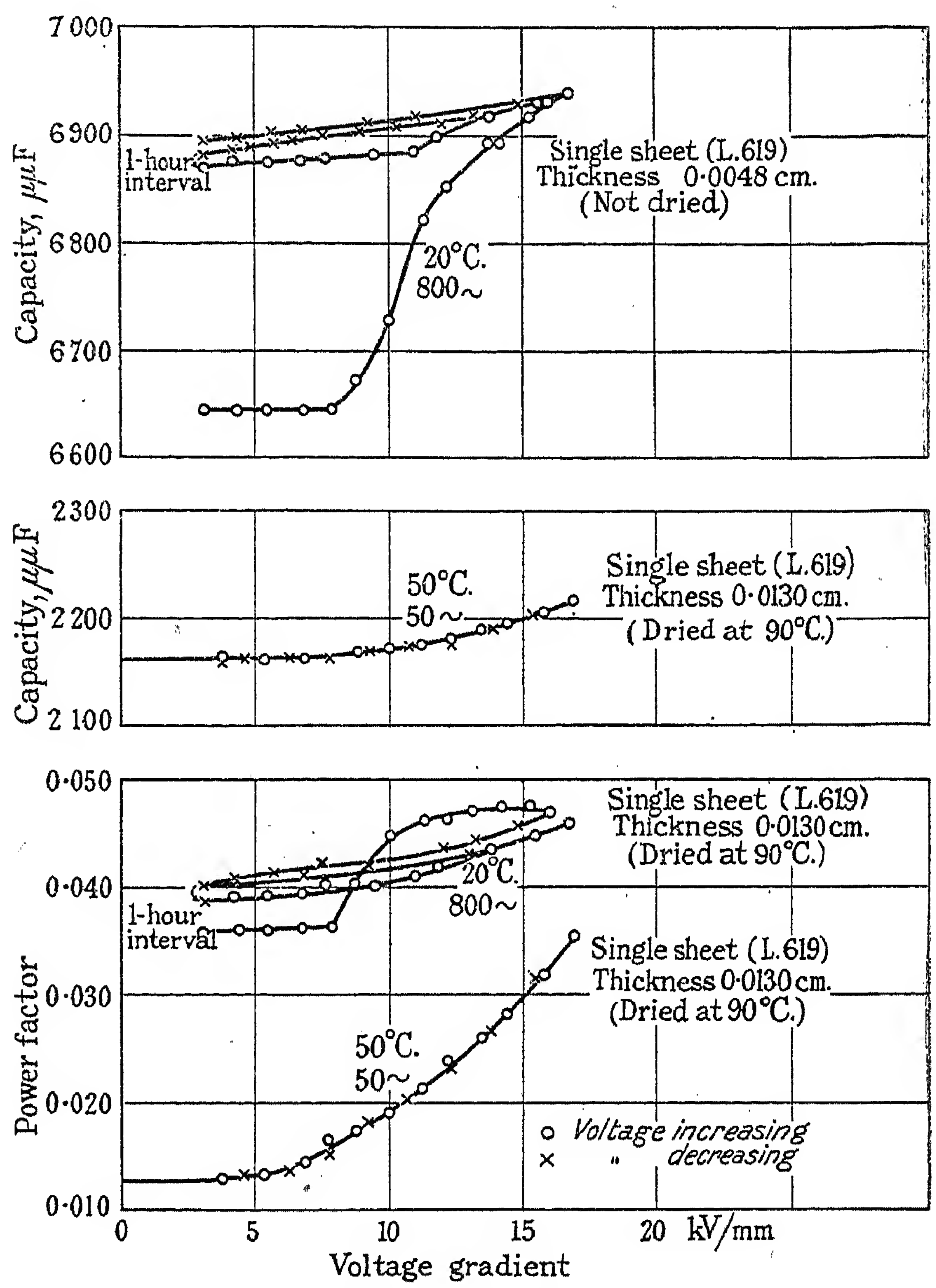

Fig. 6.—Capacitance and power factor of cellulose acetate with increasing and decreasing voltage gradient.

practically the same as the original values. To illustrate this effect, curves showing the capacitance and power-factor values with increasing and decreasing voltage gradients are shown for two samples in Fig. 6. In the one case the curves for increasing and decreasing stresses are practically identical; in the other, they are different at the lower values of voltage gradient, although if a second series of readings is taken an hour later the divergence between the curves then obtained is not so great.

In general, the mean values of capacitance and power factor with increasing and decreasing stresses were chosen.

A change in temperature of the sample during the tests will not account for this "hysteresis" effect, i.e. the

increased values of capacitance and power factor as the voltage gradient is decreased, since it has been shown that the capacitance increases and the power factor decreases with rise of temperature for low voltage-gradients. A possible explanation is that part of the increase of conductance is due to the production of new ions by the applied field, and that these ions do not immediately re-combine when the field is reduced, but that the process of re-combination is so slow that several hours are required to reach the initial condition.

Results.

The results are given in Figs. 7, 8, 9, and 10. Figs. 7 and 8 show the increase of capacitance and conductance

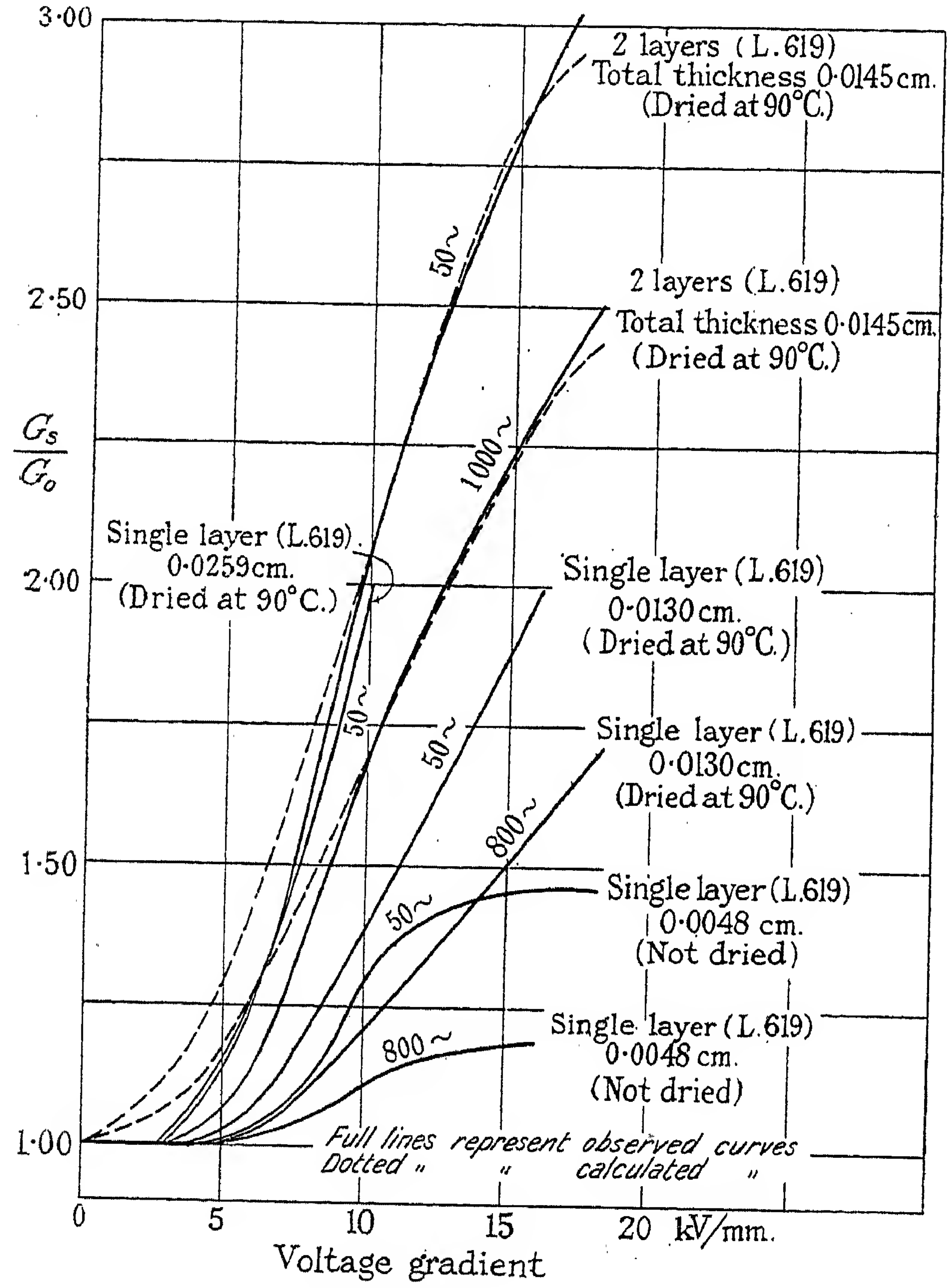

Fig. 7.—Relation between a.c. conductance and voltage gradient, showing effect of thickness at 25° C.

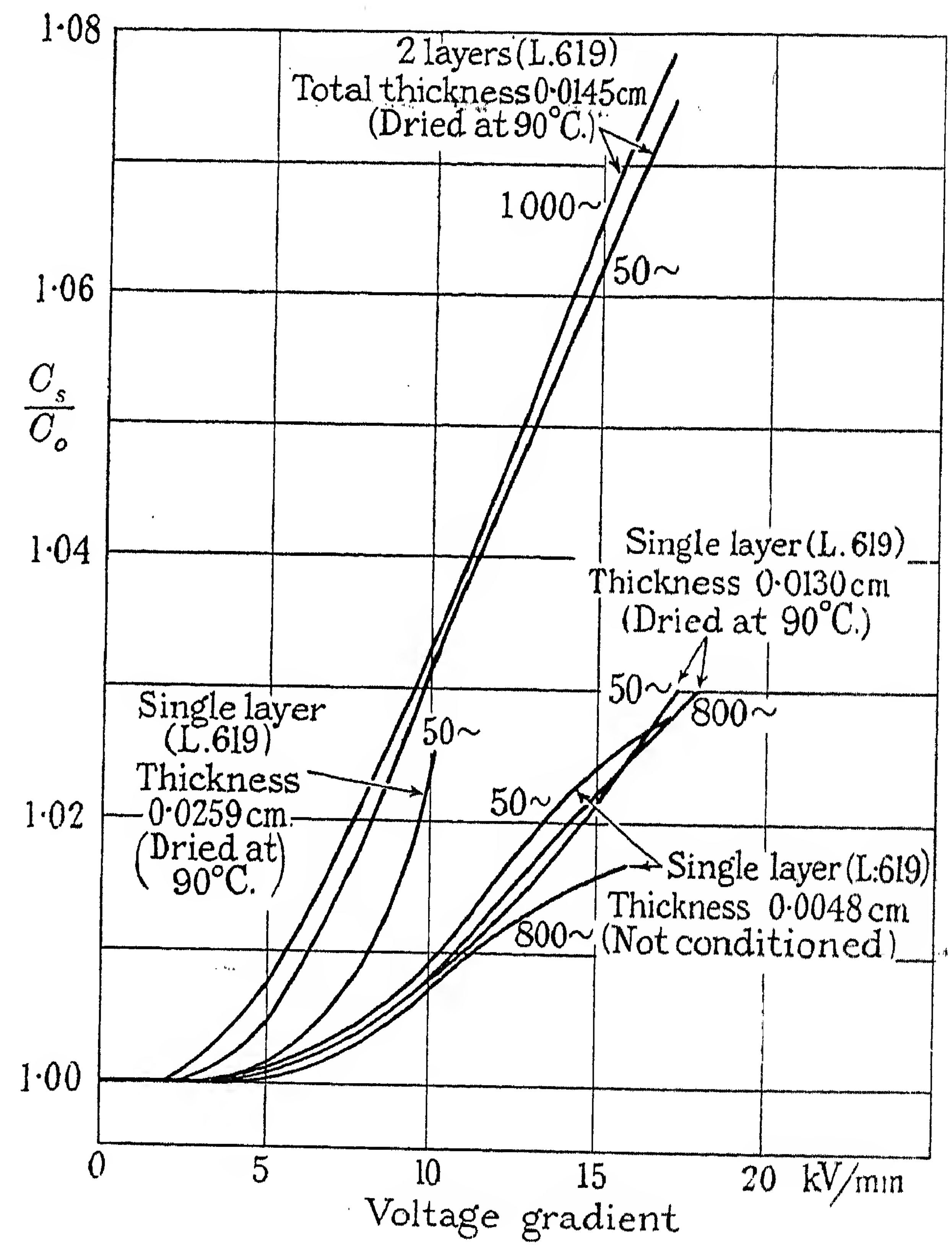

Fig. 8.—Relation between capacitance and voltage gradient, showing effect of thickness at 25° C.

with voltage gradient, the increase being represented as a fraction of the low-voltage value in each case.

The most striking feature of the results is the relatively large increase in the power factor in some cases as the voltage is raised. In one case the value is doubled at a stress of 9 kV/mm., and trebled at 17 kV/mm. The changes observed with varnished cloth were of the order of 10 per cent at 10 kV/mm. Another very significant point is the diminution in the rate of increase of conductance (or of power factor) at the highest stresses in several cases. It immediately gives rise to the suggestion that there is a tendency to approach a saturation value of some kind. The results obtained for varnished cloth were found to satisfy the equations

$$G_s = G_0(1 + pX^{\gamma}) \quad . \quad . \quad . \quad . \quad (12)$$

$$C_s = C_0(1 + qX^{\eta}) \quad . \quad . \quad . \quad . \quad (13)$$

$$W_s = G_0X^2 + pG_0X^{2+\gamma} \quad . \quad . \quad . \quad (14)$$

where G_s, C_s, and W_s are the conductance, capacitance, and power loss respectively of the sample under the voltage gradient X, G_0 and C_0 are the low-voltage values of the conductance and capacitance, and γ and η are constants of the sample. Some of the curves obtained for cellulose acetate are so different in shape from those for varnished cloth that it is immediately obvious that the above equations cannot represent all the results. Examination of the results showed, however, that up to voltage gradients of 8 or 9 kV/mm. (at which point the curves for varnished cloth come to an end), the curves for the two materials are similar, and over this range of voltage gradient the results for cellulose acetate could in general be fitted to the above equations. In two cases the equations are satisfied over the whole range of voltage gradient up to 17 kV/mm., whilst in three other cases the results cannot be accurately expressed by the equations even up to 10 kV/mm. In the latter cases the samples concerned were either at high temperature (70° C.) or were in an undried condition.

The values of the constants γ, η, p, and q obtained from equations (12) and (13) are given in Table 4. It will be observed that the values of the indices γ and η are of the same order as those found for varnished cloth.

The mean values are $\gamma = 3 \cdot 4$, $\eta = 3 \cdot 2$. It is therefore not improbable that in spite of the great difference in the magnitude of the phenomenon in the two cases the physical process involved is similar, and that if the voltage gradient to which the varnished cloth were subjected could be increased to still higher values the rate of increase of conductance would not be expressed by the above equations over the whole range of voltage gradient.

It was found that, in those instances where equations (12) to (14) did not hold over the range of voltage gradient 8 to 18 kV/mm., the conductance of the samples could be expressed with considerable accuracy by the formula

$$G_s = A + B \log X$$

from which it follows that $\dfrac{dG_s}{dX} = \dfrac{B}{X}$

In other words, over this range the rate of increase of conductance with electric stress is inversely proportional to the value of the stress.

The variation of permittivity with stress is shown in Fig. 8. Here again the change is very much larger than it was for varnished cloth, though the curves for the two materials are similar in shape up to the point at which the curves for varnished cloth terminate. Beyond this point the increase of permittivity of cellulose acetate with stress is approximately linear in some cases. In others it follows equation (13), and there are also cases in which the rate of increase diminishes as the stress is increased.

The effect of frequency on the increase of conductance and permittivity with voltage gradient may be judged from Figs. 7 and 8. The ratio of high-voltage to low-voltage conductance G_s/G_0 is of the same order at frequencies of 50 cycles and 800 or 1 000 cycles, although the actual values of the two conductances are about 20 times as great at 1 000 cycles as they are at 50 cycles. There is, however, a definite tendency for the ratio G_s/G_0 to diminish as the frequency increases. The effect of voltage on permittivity appears to be almost indedependent of frequency, at any rate for dried material.

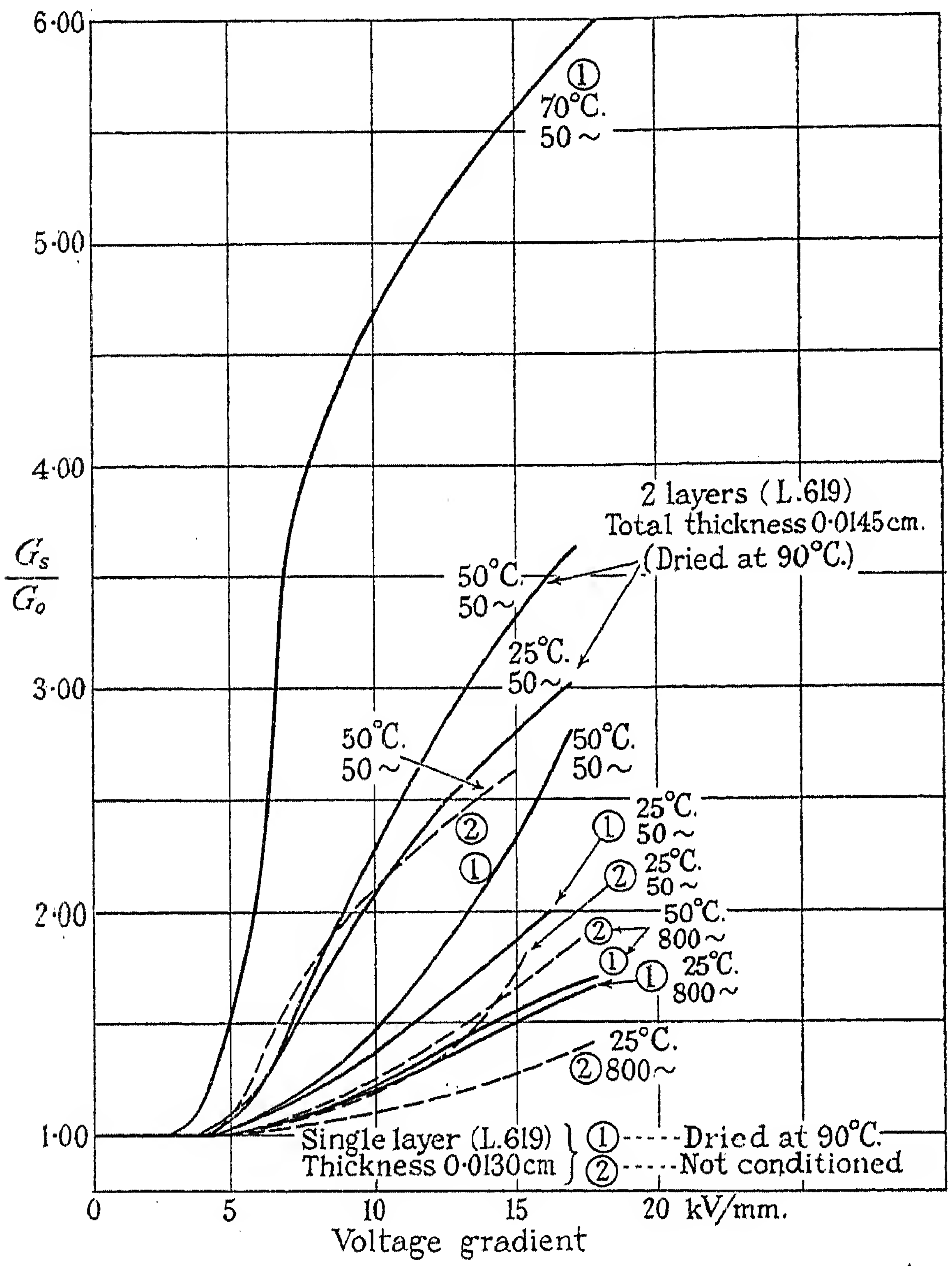

Fig. 9.—A.C. conductance and voltage gradient, showing effect of temperature and drying.

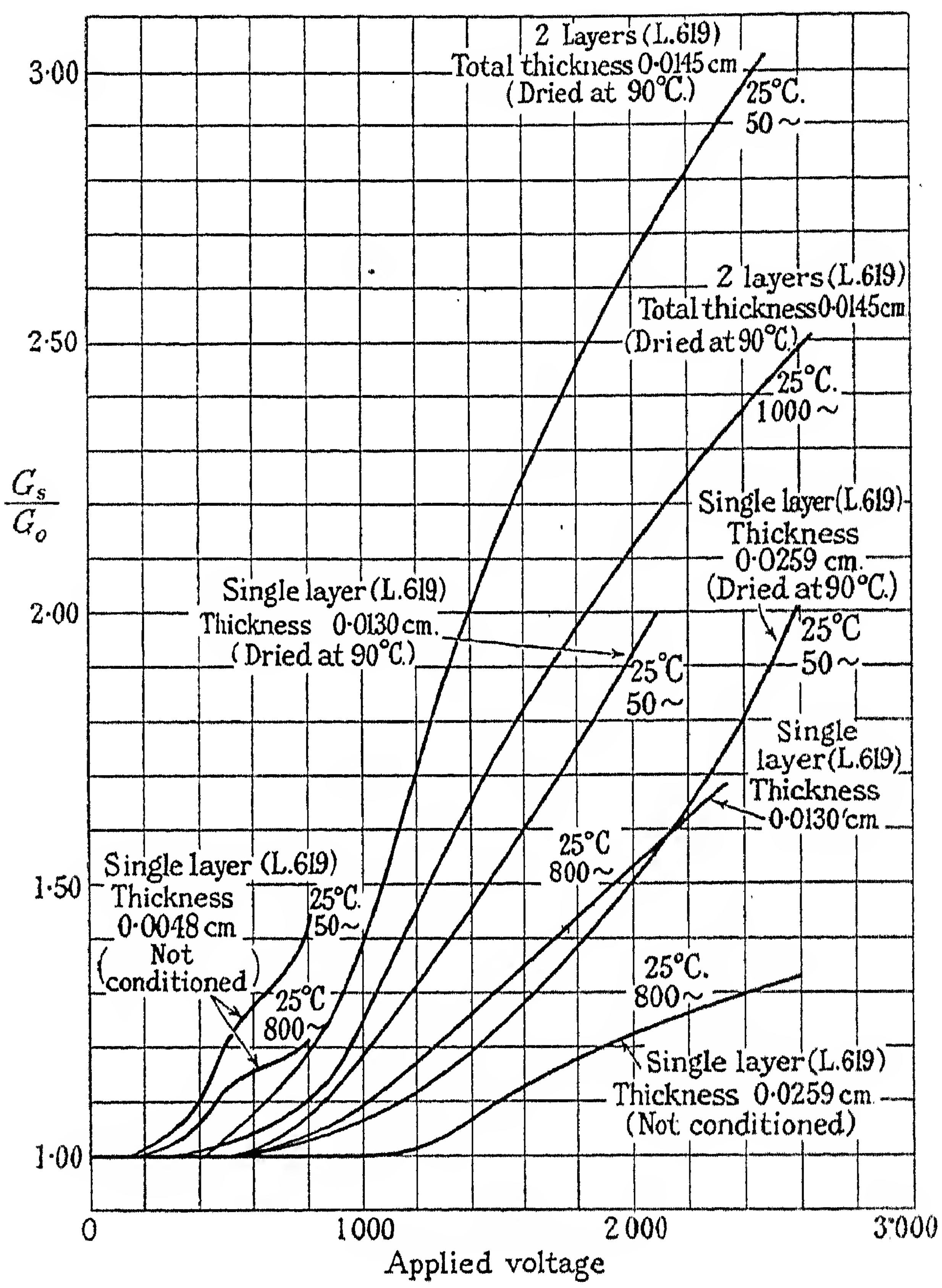

Fig. 10.—A.C. conductance and applied voltage, showing effect of thickness.

The effect of temperature on the increase of conductance with voltage gradient is shown in Fig. 9. Generally speaking, the effect of a rise in temperature from 25° to 50° C. is to cause a small increase in the ratio G_s/G_0. A further rise of temperature to 70° C. made in one case caused a large increase in G_s/G_0, the conductance at a stress of 17 kV/mm. becoming six times as great as the low-voltage value. It is worthy of note that, while at a stress of 4 kV/mm. the conductance at 20° C. is twice as great as that at 70° C., yet with a stress of 17 kV/mm. the conductance at 70° C. is 50 per cent greater than that at 20° C. This fact is of considerable importance in considering the possibility of

Table 4

VALUES OF γ, η, p, AND q, IN THE EQUATIONS:

$$W = G_0X^2(1 + pX^\gamma) \quad . \quad . \quad . \quad (14)$$

and $$C = C_0X^2(1 + qX^\eta) \quad . \quad . \quad . \quad (13)$$

Sample	Temp., °C.	Frequency: cycles/sec.	γ	η	p	q	Notes
L 619. Two layers Total thickness, $0{\cdot}014_5$ cm. Dried at 90° C.	25	50	3·1	2·4	9×10^{-4}	1×10^{-4}	(*a*), (*b*)
	25	1 000	3·5	2·1	2×10^{-4}	3×10^{-4}	(*a*), (*b*)
	50	50	4·3	2·6	$0{\cdot}6 \times 10^{-4}$	$0{\cdot}5 \times 10^{-4}$	(*a*), (*b*)
L 619. Single sample Thickness, $0{\cdot}025_9$ cm. Dried at 90° C.	25	50	2·9	4·1	14×10^{-4}	$1{\cdot}9 \times 10^{-6}$	(*a*)
L 619. Single sample Thickness, 0·0130 cm. Not dried	25	50	3·2	4·0	$1{\cdot}3 \times 10^{-4}$	$2{\cdot}6 \times 10^{-7}$	(*c*)
	25	800	2·9	3·2	$1{\cdot}2 \times 10^{-4}$	$2{\cdot}2 \times 10^{-6}$	(*c*)
	50	50	Equations do not hold.				
	50	800	3·8	4·3	$0{\cdot}4 \times 10^{-4}$	$0{\cdot}7 \times 10^{-6}$	(*a*), (*b*)*
L 619. Single sample Thickness, 0·0130 cm. Dried at 90° C.	25	50	3·3	3·0	$1{\cdot}9 \times 10^{-4}$	$8{\cdot}8 \times 10^{-6}$	(*a*)
	25	800	3·0	3·0	$2{\cdot}3 \times 10^{-4}$	$9{\cdot}5 \times 10^{-6}$	(*a*), (*b*)
	50	50	4·1	3·5	$0{\cdot}3 \times 10^{-4}$	$1{\cdot}3 \times 10^{-6}$	(*a*), (*b*)
	50	800	3·0	3·0	$2{\cdot}2 \times 10^{-4}$	$5{\cdot}3 \times 10^{-6}$	(*a*), (*b*)
	70	50	Equations do not hold.				
L 619. Single sample Thickness, $0{\cdot}004_8$ cm. Not dried	25	50	3·6	2·8	$0{\cdot}7 \times 10^{-4}$	$0{\cdot}2 \times 10^{-4}$	(*a*)*
	25	800	Equations do not hold.				*
		Mean . .	3·4	3·2			

* Hysteresis effect pronounced.

NOTES: (*a*) Equations (13) and (14) apply up to gradient of 10 kV/mm. approx.
(*b*) Equation $G_s = A + B \log X$ applies from 10 to 17 kV/mm.
(*c*) Equations (13) and (14) apply over whole range to gradient of 17 kV/mm.

thermal instability in the material. A rise of temperature also affects the rate of increase of conductance with voltage gradient; it will be observed from Fig. 9 that the tendency of the rate of increase of conductance with stress (dG/dX) to diminish at the highest stresses is more marked at the higher temperatures.

Fig. 9 also gives some information on the effect of moisture content on these phenomena. At low temperatures the ratio G_s/G_0 for a given stress is greater for dried material than for undried, but the ratio increases more rapidly with temperature for the undried material, and at 50° C. is greater for this material than for the dried material.

A comparison of the results obtained with samples of different thickness is of importance. Fig. 7 shows the results obtained at 25° C. with samples of thickness varying from 0·0048 cm. to 0·0259 cm., and it is immediately obvious that in all cases the increase of conductance begins at a fairly definite voltage gradient (3 to 4 kV/mm.), which suggests that voltage gradient (and not total voltage) is the determining factor. On the other hand, voltage gradient is not the only factor involved, since the curves are very different for samples of different thickness. For single-layer samples the ratio G_s/G_0 for a given voltage gradient increases with the thickness. A sample of two layers gives a greater increase in the ratio G_s/G_0 than a single-layer sample of the same total thickness. Variations in the material in samples of different thickness may account for some of these differences; for example, their power factors varied as shown in Table 5, but it is more than possible that the increase of conductance under high voltage depends

Table 5

POWER FACTOR OF SAMPLES USED IN HIGH-VOLTAGE MEASUREMENTS

CELLULOSE ACETATE L 619

Condition	Number of layers	Total thickness, cm.	Power factor at 25° C., 800 cycles	Power factor at 25° C., 50 cycles	Power factor at 50° C., 50 cycles
Not dried	1	0·0048	0·0359	0·0279	—
Not dried	1	0·0130	0·0300	0·0202	0·0183
Dried . .	1	0·0130	0·0272	0·0195	0·0130
Dried . .	2	0·0145	0·0283*	0·0193	0·0134
Dried . .	1	0·0259	—	0·0223	—

* Value at 1 000 cycles.

on the total thickness and the number of layers, as well as the voltage gradient even for material of the same composition. The results were also plotted against total voltage (Fig. 10), but the curves obtained were more widely different than those obtained by plotting against voltage gradient, so that total voltage cannot be regarded as the determining factor. One might be tempted to conclude that the large increase in the conductance of the sample of two layers was due to the ionization of an air film between them, but it is unlikely that such ionization would begin at just that critical voltage gradient which applies to the single-layer samples. Also the power factor of the two-layer sample was not greatly different from those of one layer (see Table 4), so that any air film present must have been extraordinarily thin.

which had previously been used for the a.c. measurements. This sample, after drying at 90° C., was tested at 25° C. with voltage gradients up to 19 kV/mm. On raising the temperature to 50° C., however, the sample broke down under a stress of 17 kV/mm.

In both these series of measurements, the final conductance alone was observed as it was difficult to get sufficient steadiness of conditions to allow satisfactory measurements of absorption current to be made.

Results.

The results are shown in Fig. 11, from which it may be seen that the relation between final conductance K and voltage gradient X is approximately linear, and we may write

$$K = K_0(1 + mX) \quad . \quad . \quad . \quad . \quad (15)$$

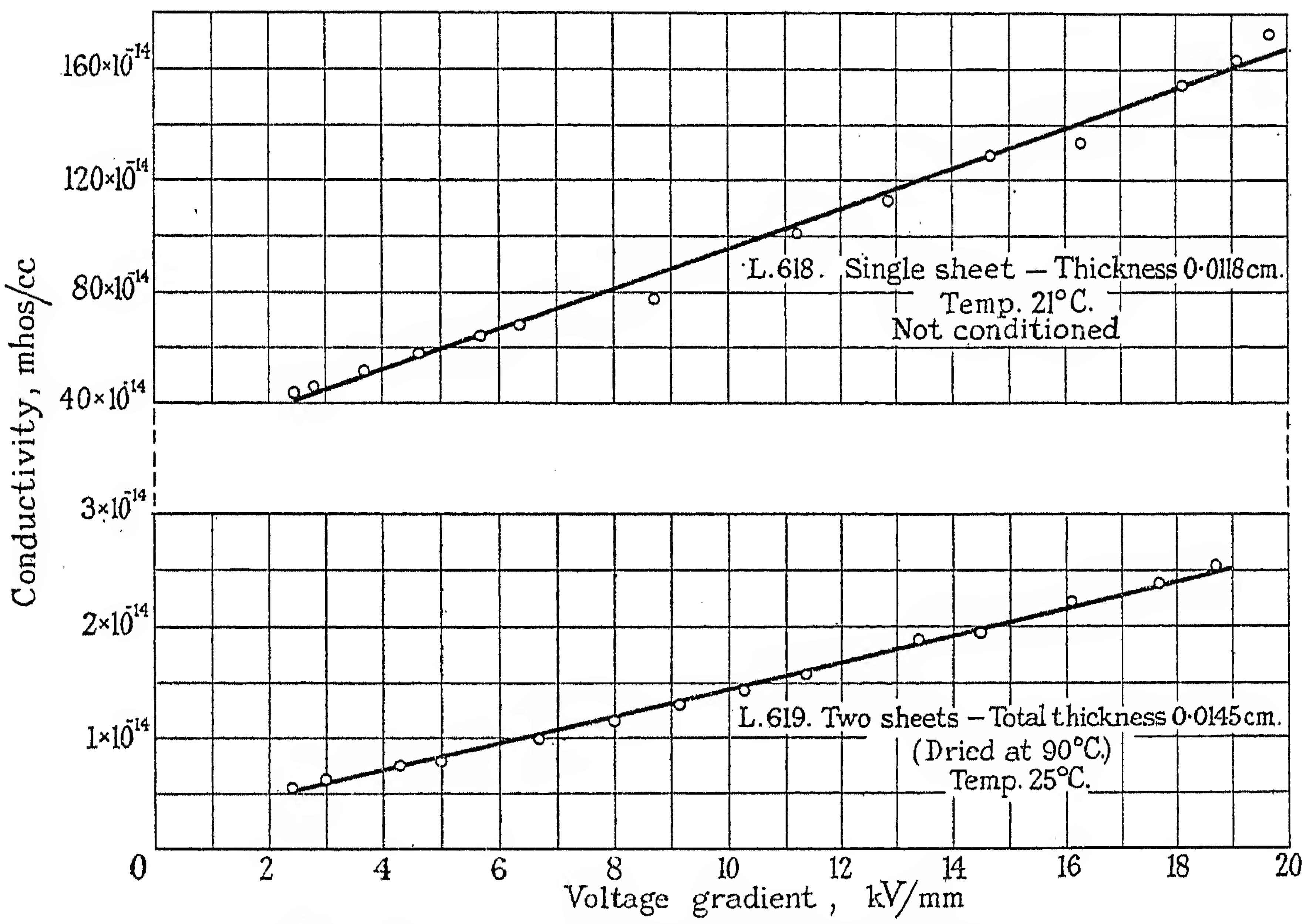

Fig. 11.—D.C. conductivity and voltage gradient.

(5) HIGH-VOLTAGE D.C. MEASUREMENTS

Measurements were also made to find out whether the properties of the material under d.c. conditions varied with the applied stress in the same way as did the a.c. properties. The method and apparatus were exactly the same as those used in the investigation on varnished cloth (see Ref. L/T44).* As in the case of the a.c. measurements, it was difficult to get satisfactory results owing to the breakdown of several samples under voltage gradients of about 15 kV/mm. or less, before the tests were finished. Eventually two complete series of observations were obtained and these were considered to be sufficient for our purpose. The first was for a sample of material L 618 under ordinary room conditions, i.e. without drying or conditioning in any way. This sample was afterwards dried at 90° C., allowed to cool and tested at 25° C., when it broke down under a stress of only 9 kV/mm. The second series of measurements was obtained on the two-layer sample of material L 619,

* *Journal I.E.E.*, 1934, vol. 75, p. 631.

The deviations from this law are probably no greater than the experimental error. Thus the behaviour of cellulose acetate under these conditions is very similar to that of varnished cloth, although the values of the coefficient m for cellulose acetate are considerably larger than those for varnished cloth (see Table 7).

It is to be observed that the rate of increase of final d.c. conductance with voltage is relatively much greater than the corresponding increase of a.c. conductance, each being expressed in terms of its low-voltage value. Thus the d.c. conductance at 18 kV/mm. is about ten times as great as the low-voltage value, while the a.c. conductance is about three times as great as its low-voltage value under the same stress. Since the final d.c. conductance also increases with rise of temperature, while the a.c. conductance in some cases does not,* it seems probable that as breakdown conditions are approached the final conductance becomes more and

* However, at very high stresses, the a.c. conductance does increase with rise of temperature (see page 325).

Table 6

Time from application of voltage (min.)	Conductance, mho			Ratio: $\frac{K_{2v}}{K_v}$	Ratio: $\frac{K_{3v}}{K_v}$
	At 0·3 kV/mm. (K_v)	At 1·1 kV/mm. (K_{2v})	At 2·2 kV/mm. (K_{3v})		
1	$3{\cdot}25 \times 10^{-10}$	$3{\cdot}41 \times 10^{-10}$	$3{\cdot}55 \times 10^{-10}$	1·05	1·09
2	$3{\cdot}20 \times 10^{-10}$	$3{\cdot}40 \times 10^{-10}$	$3{\cdot}53 \times 10^{-10}$	1·06	1·10
10	$3{\cdot}17 \times 10^{-10}$	$3{\cdot}34 \times 10^{-10}$	$3{\cdot}49 \times 10^{-10}$	1·05	1·10

more important, and that the actual breakdown is a process of simple d.c. conductance, under the conditions of these experiments, i.e. for frequencies less than 1 000 cycles per sec.

It has been observed that the a.c. conductance is practically independent of the voltage for voltage gradients less than 3 kV/mm. (approx.).

Measurements were made to determine whether the d.c. conductance was similarly independent of stress at the lower voltage gradients. A sample of the material L 619 of thickness $0{\cdot}018_0$ cm. was tested at voltages of 50, 200, and 400 supplied from batteries. With the direct deflection method used, the galvanometer readings obtained are only small at low temperature and with dried materials, so the sample was not conditioned and

Table 7

	Temperature, °C.	σ_0	m
Sample L 618 . . . . Thickness, 0·0118 cm. Not conditioned	21	22×10^{-14}	0·29
Sample L 619 . . . . Two samples Total thickness, $0{\cdot}014_5$ cm. Dried at 90° C.	25	$0{\cdot}2 \times 10^{-14}$	0·67

the temperature of test was raised to 50° C. By this means greater deflections were obtained.

Measurements of the conductance at 1, 2, and 10 minutes from the time of application of the voltage are given in Table 6.

It will thus be seen that the conductance increases when the voltage gradient is increased, even for these low gradients. The relation $K = K_0(1 + mX)$ may again be used, but the value of m is in this case only 0·05. It therefore appears that the d.c. conductance differs from the a.c. conductance in that it is not independent of the voltage gradient for gradients below 3 kV/mm. The small value of m in this case may be due to the high temperature, but as the experiments on this sample were not carried to high-voltage gradients it is not possible to say whether or not the rate of variation of K is constant over the whole range of voltage gradient.

(6) DISCUSSION OF RESULTS

The Mechanism of the Dielectric Absorption.

We have shown that the power loss in this material under low voltage-gradients, or, in other words, its a.c. conductance, is almost entirely due to dielectric absorption, or a displacement of electrical charges within the material, which conforms to the superposition principle. There are many theories which might possibly be applied, but since the material is clear and transparent, and has been freed as completely as possible from water, one must, in this case, rule out Maxwell's theory and its modifications, which assume inhomogeneity of the material on a large scale. Since also the properties of the material at low voltage-gradients do not depend to any important extent on the thickness of the sample tested, it is probable that theories depending on the accumulation of ions at the outer surfaces do not apply to this material. We are left with Debye's dipole theory, and the theory of adsorbed ions proposed by Murphy and Lowry,* as the most probable. According to the dipole theory, the electrical displacement is due to molecules of the material, which are electrically unsymmetrical, and therefore possess a permanent electrical moment. Under the influence of an applied field, these molecules tend to take up a definite orientation. Their motion is opposed by a force of viscosity and is therefore retarded, the result being a dissipation of power in alternating fields and absorption currents in constant fields. It has been shown by Kitchin and Muller† that this theory can be successfully applied to certain results for resin and castor oil, and by Race‡ that it may be similarly applied to mineral oils. There seems to be no reason why it should not also apply to the same extent to cellulose acetate. According to the theory, the power factor increases with increasing frequency up to a maximum value at a certain frequency, which is determined by the molecular constants of the material. A further increase of frequency causes a decrease of power factor. The effect of a change of temperature is merely to cause a displacement of this maximum value to a higher frequency, the general form of the power-factor/frequency curve being unaltered. It

* *Journal of Physical Chemistry*, 1930, vol. 34, p. 598.
† *Physical Review*, 1928, vol. 32, p. 979.
‡ *Ibid.*, 1931, vol. 37, p. 430.

follows that the increase of the power factor of the material with increasing frequency, and its decrease with rising temperature, are both consistent with the theory, provided that the frequency which is characteristic of the molecular movement (i.e. at which the maximum power factor occurs) is greater than those used in this investigation. This is, of course, highly probable. If, however, we attempt a quantitative check of the theory by means of our observations, we are immediately faced with a discrepancy. The theory in its simple form predicts an a.c. conductance which is given by an equation of the form

$$G = \frac{P\omega^2}{Q + R\omega^2} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

from which it follows that $\omega/(C \tan \delta)$ should be a linear function of ω^2. The authors' observations certainly did not satisfy the relation, so that although the dipole mechanism will account for certain features of the results, it does not give anything approaching a complete explanation.

The picture given by Murphy and Lowry for the dielectric phenomena occurring in materials such as cellulose acetate is as follows. The substance is built up of a number of minute structural units, each containing, say, 10^4 molecules. Each unit is regarded as a perfect insulator; dielectric imperfections are confined to the spaces between the units, and any water which may be absorbed is accumulated there. These spaces may be regarded as conducting closed surfaces, insulated from one another, and the movement of ions on the surfaces is the cause of conduction and dielectric absorption. Ions which are adsorbed, and which therefore cannot leave the particular surface to which they are attached, give rise to dielectric absorption. Free ions lead to conduction. It may be shown that the displacement of the adsorbed ions thus pictured conforms to the superposition principle, and that it will therefore in some measure account for the results obtained for the power loss and absorption currents in cellulose acetate. A close quantitative agreement can only be obtained, however, on the assumption that there are several kinds of ions, bound to the conducting surfaces by forces of different magnitudes. The diminution of the power loss due to dielectric absorption with rise of temperature is explained by Murphy and Lowry as being due to the liberation of some of the adsorbed ions as the forces of thermal agitation increase, and this also would account for the increase of d.c. conductivity under the same conditions, although the two quantities are of such different orders of magnitude that it is difficult to accept this explanation. There remains, however, the possibility of accounting for the variations of power loss with temperature and frequency, not by change in the number of adsorbed ions, but by a change in their relaxation times, exactly similar to the change in the relaxation times of the polar molecules. The same analysis would apply to both processes, and it is not possible to discriminate between them by a consideration of the results of the low-voltage experiments. It may be recalled that the effect of a trace of moisture on a sample at 90° C. was to increase its final conductance and to diminish its absorption conductance, both by very large amounts. On Murphy and Lowry's picture this means that the water liberates certain of the adsorbed ions, a process which appears to be not improbable.

The Mechanism of the Increase of Conductivity with Stress.

In our report on the properties of varnished cloth under high-voltage gradients, various processes have been considered in order to explain the increase of conductivity with rise of voltage gradient. These include the movements of water in the capillaries of the structure according to Evershed's theory, and ionization by collision. The application of Evershed's theory to the results for cellulose acetate is out of the question since the material is not fibrous, and it was thoroughly dried. The process of ionization by collision in solids, on the lines of Townsend's theory for gases, has been considered by Gunther-Schulze* and in more detail by S. Whitehead,† who have shown that it would cause an increase of conductivity, which would depend not only on the voltage gradient but also on the total voltage. Although certain features of the present results are not inconsistent with this view, e.g. the increase of power loss with stress does not seem to be greater for a given field strength for thick specimens than for thin ones, also the hysteresis effect observed with the very thin material suggests that at least some new ions are produced at high stresses, yet the fact that the rate of increase of conductivity in some cases definitely diminishes as the field is increased, and that there is a tendency to approach a saturation value, appears to be inconsistent with the theory of ionization by collision. It would, however, be consistent with the authors' previous suggestion that the effect of the ionic collision is to detach associated neutral molecules from the ions and so increase their velocity. Such a process would obviously lead to a saturation value of conductivity.

The increase of a.c. conductivity appears to be approximately proportional to the low-voltage value of the conductivity, from which it seems probable that the process by which this increase occurs, whatever its nature, must operate on the electrical carriers which take part in the low-voltage conductance. Thus, if the a.c. conductance were due to the rotation of polar molecules we should expect its increase with voltage gradient to be due also to these molecules. We should expect, however, the rotation per unit field of a polar molecule to decrease with increase of the field, since the rotation cannot exceed a certain finite limiting value. Thus the evidence of the high-voltage experiments suggests that the conductance of cellulose acetate, both a.c. and d.c., is not due to the movements of dipoles, but to those of ions.

Some recent work on the properties of ionic systems will now be considered.

The Theory of Inter-Ionic Attraction.

In recent years it has been found that the conduction of electrolytic solutions does not obey Ohm's law when the applied electric field is increased from the low values generally used in work on electrolytes, to values of the order 10 kV/mm., i.e. the order of voltage gradient employed in the present investigation. When our

* *Physikalische Zeitschrift*, 1923 vol. 24, p. 212. † Unpublished.

results are compared with those obtained with electrolytic solutions, certain points of resemblance become obvious, so that it is important to consider to what extent the theories developed to explain the behaviour of electrolytes may be applied to dielectrics.

The results of two independent lines of experimental work are available. M. Wien* has studied the conduction of aqueous solutions of strong electrolytes, such as potassium chloride and magnesium sulphate. The power dissipated in such materials under high-voltage gradients is, of course, very great, and in order to avoid a rise of temperature due to this cause, Wien worked with voltage-impulses of very short duration (of the order 10^{-6} sec.). He found that under these conditions the conductivity of the solution increased with the applied field, the curve representing the increase being strikingly similar to some of the curves representing the authors' a.c. results for cellulose acetate, namely, those which bend over at the highest voltage gradients.

An investigation of a rather different type has been carried out by Gyemant.† He used solutions of much lower conductivity, e.g. picric acid dissolved in a mixture of benzene and ethyl alcohol. Thus the difficulty of self-heating was less important in this case, and he was able to employ the ordinary d.c. method of determination of resistance by observations of current and voltage. He also observed an increase of conductance with increasing voltage gradient, and describes his results as being similar to those of Wien. An examination of his curve shows, however, that it resembles much more closely the authors' d.c. results than their a.c. results, e.g. his curve shows no tendency to approach a limiting value at the highest voltages.

The most satisfactory theory of these effects is one put forward by Debye and his associates, showing that they are a consequence of the electrostatic forces of attraction or repulsion acting between each pair of ions in accordance with Coulomb's law. Since each positive ion attracts all the negative ions in its neighbourhood and repels all the positive ones, it tends to surround itself with more negative ions than positive ones. Thus in any medium containing free ions in a state of agitation there will be a certain regularity in the distribution of positive and negative ions. In the development of the theory this regularity is represented by considering each ion to be surrounded by an atmosphere of ions of opposite sign, and it is shown that these ionic atmospheres must be regarded as possessing a certain effective radius, of the order $10^{-8}/\gamma$ cm., and a certain characteristic time constant of the order $10^{-10}/\gamma$ sec., where γ is the concentration of ions in mols per litre. The time-constant τ or time of relaxation represents the natural time of formation and disintegration of the atmosphere. For example, if an ion is suddenly removed from a certain position the time required by its neighbours to assume a random distribution is characterized by τ. As a result of the presence of the atmosphere and its finite time of formation, the motion of each ion must be regarded as being opposed by other forces besides that due to the viscosity of the fluid medium, and given by Stokes's law. Thus Stokes's law applies only to an uncharged medium, but the existence of the ionic atmosphere implies that the elements of volume of the medium nearest to the ion must be regarded as charged, and an additional force is called into play on this account. This force is usually called the force of electrophoresis. It may be regarded as an addition to the force given by Stokes's law. Again, the atmosphere of an ion which is not drifting under the action of an external field may be regarded as possessing spherical symmetry, so that the force between the ion and its atmosphere has the same value in every direction, but when the ion begins to drift under the action of a field this symmetry is destroyed owing to the finite time required for the atmosphere to assemble and disintegrate at the points successively occupied by the ion in its motion. It is almost as though there were a slight lag between the ion and its atmosphere (though the motion of the atmosphere must be thought of as like that of a wave and not as one of translation of the ions forming it). The result is that the force exerted by the atmosphere on the ion is no longer the same in all directions; there is a resultant force in the opposite direction to the motion of the ion. This force is often called the relaxation force. Thus the motion of an ion must be regarded as opposed by three forces—that due to the ordinary viscosity of the medium (the Stokes's force), the relaxation force, and the electrophoresis force. The mathematical theory of the motion of an ion under the influence of these forces shows that to a first approximation the velocity is proportional to the applied field. Thus the conductivity is independent of the field, and Ohm's law holds for weak fields. A second approximation shows, however, that the relation between conductivity G and applied field X should be represented by the formula*

$$\Delta = \frac{G - G_0}{G_0} = AX^2(1 - \beta X^2) \quad . \quad . \quad (17)$$

or

$$G = G_0[1 + AX^2 - \beta AX^4] \quad . \quad . \quad (18)$$

Thus the conductivity should increase with the applied field, and in its early stages this increase should be given by the above formula. If now the applied field becomes very great, the velocities of the ions may become so large that an ion does not occupy any one position for a sufficient time to allow the atmosphere to collect. Thus the forces of relaxation and electrophoresis no longer exist and the mobilities of the ions are correspondingly increased. In fact, in very high fields the conductivity tends to approach a limiting value, which is the value obtained when the Stokes's force only is opposing the motion of the ion. On this theory the values of the conductivity at very low and very high voltages give some idea of the relative magnitudes of the inter-ionic forces and those of ordinary viscosity. Very good agreement has been obtained between the above theoretical equation and Wien's experimental results for various electrolytes. The theory has also explained the variation of the equivalent conductivity of solutions with dilution, so that there is no doubt that the forces described must be considered in any discussion of systems of free ions, and there is a probability of their being important in dielectric theory.

* *Physikalische Zeitschrift*, 1928, vol. 29, p. 751.

† *Wissenschaft Veröffentlichungen aus dem Siemens-Konzern*, 1928, vol. 7, p. 134.

* G. Joos: *Physikalische Zeitschrift*, 1928, vol. 29, p. 755.

Application to Cellulose Acetate.

It will be obvious that the above theory supplies at least a possible explanation of the authors' results for cellulose acetate. It gives an increase of conductance, which is a function of voltage gradient only and not total voltage. This increase is proportional to the low-voltage conductivity and at very high field strengths the rate of increase diminishes, the conductivity tending towards a limiting value in the highest possible fields. However, the authors were not able to obtain a very good agreement between their results and equation (17), which might be expected to represent the initial portion of the curves of Fig. 7. The dotted lines in this diagram represent equation (17), when the constants are chosen so as to fit the portion of the curves between 10 and 17 kV/mm. Attempts made to fit the formula to the parts of the curves between 3 and 8 kV/mm. all gave negative values for β, and it is doubtful whether the formula can be applied to these results. The values of the constants are of some interest. Those for the dotted curves of Fig. 7 are of the order $A = 1 \times 10^{-10}$, $\beta = 1\cdot4 \times 10^{-11}$. Wien's values for various electrolytes were of the order $A = 2 \times 10^{-11}$, $\beta = 3 \times 10^{-11}$ (in calculating all these values, the field strength was expressed in volts per cm.). Thus the constants are of the same order in the two cases, though actually the relative increase of conductivity of cellulose acetate was much greater than any observed by Wien, which would suggest that the inter-ionic forces are relatively greater in cellulose acetate. Possibly this could be accounted for by the small dielectric constant of the material.

The Effect of Frequency.

In the foregoing account of this theory, no mention has been made of frequency. Direct-current conditions have been implied, and yet the theory has been considered in relation to a.c. observations. This obviously requires further consideration.

We have seen that the relaxation force opposing the motion of an ion depends on the finite time required for the formation and dissipation of the ionic atmosphere at any point, as a result of which there is a kind of lag between a moving ion and its atmosphere. It will be obvious that such an effect will depend on frequency, at any rate in the region over which the periodic time is of the same order as the time of relaxation of the ionic distribution. Debye and Falkenhagen* have investigated this effect mathematically and have shown that the conductivity must increase with the frequency and at the same time the dielectric constant must decrease with frequency. In other words, the effects are those of dielectric absorption, and we may regard the theory of inter-ionic attraction as another possible explanation of the results obtained for power loss and permittivity at various frequencies. The curves of conductivity and permittivity against frequency are very similar to those given by the other theories. The only important difference between the various curves is the frequency scale, and if in each case the frequency unit is proportional to the relaxation time of the system under consideration the curves are practically identical. The relaxation times of a dipole system, an ionic atmosphere, and a structural unit of Murphy and Lowry's picture, may, of course, be of quite different orders of magnitude, and this fact may be of use in discriminating between the various processes. For example, the calculations of Debye and Falkenhagen give a value of the order of 10^{-7} sec. for the time of relaxation of an aqueous solution of molar concentration $0\cdot001$. Thus dielectric absorption effects should be most noticeable in such a solution at frequencies of the order 10^7 cycles per sec. It is interesting to note that when the frequency becomes very high compared with $1/\tau$ the ion vibrates so fast that the atmosphere is quite unable to adapt itself to the movement. It may be considered as stationary with the ion vibrating about its centre. The mean force exerted by the atmosphere on the ion is now the same in all directions, i.e. the relaxation force has vanished. Thus as the frequency becomes higher and higher (at low voltages) the conductivity increases, ultimately approaching a limiting value, which is the value obtained when the relaxation force becomes zero. The limiting value for very high voltage-gradients will be higher than this high-frequency value, since at high voltage-gradients the electrophoresis force also vanishes. The two limiting values would therefore give some idea as to the relative importance of the relaxation force and the electrophoresis force. It is also interesting to notice that if the high-voltage experiments are carried out at a high frequency, the increase of conductivity with voltage should be smaller.

When the frequency is very low compared with $1/\tau$ we may consider that the ionic atmosphere is able to follow every movement of the ion, and thus the mobility of the ion is the same as under d.c. conditions. Thus the a.c. and d.c. values of conductivity should be identical as long as the frequency is negligibly small compared with $1/\tau$, which is the condition assumed in the discussion of the voltage effect.

* *Physikalische Zeitschrift*, 1928, vol. 29, p. 401.

(7) CONCLUSIONS AND RECOMMENDATIONS

Conclusions.

A general survey of the experimental results for cellulose acetate points to the conclusion that the dielectric properties of this material can only be explained by a combination of several of the processes which have been considered. Thus the dominating factor in the determination of the power losses in the material under low voltage-gradients appears to be a process characterized by a time of relaxation considerably less than 10^{-3} sec. The fact that the conductance representing these losses increases with the voltage gradient suggests that the process is one of ionic conduction, and that the increase of effective conductance with voltage gradient is due to the change in the inter-ionic forces resulting from the increased velocities of the ions in accordance with the developments of Debye's theory. The effect of the voltage gradient is complicated by the fact that the time of relaxation may not be negligibly small compared with the periodic time of the applied voltage. The variation of the power loss with frequency shows that a single process with one time of relaxation is not sufficient to account for the results. There must be several such processes with different times of relaxation. The d.c. absorption currents after a time of charge of 10 or

100 seconds show that there must be at least one process with a time of relaxation of this order. Such large time-constants are much more likely to be associated with large groups of molecules than with single ions. The authors are therefore inclined to think that a mechanism such as that proposed by Murphy and Lowry must be responsible for the d.c. observations, i.e. the conduction is ionic and takes place not uniformly throughout the material but along certain restricted paths. On this theory the final d.c. conductance is due to the motion of the free ions only. Its increase with voltage gradient might possibly be accounted for by the liberation of adsorbed ions by the field as suggested by Murphy and Lowry, but the similarity of the present results to those of Gyemant, which were obtained for liquids containing ions, suggests that the increase of conductance is not due to an increase in the number of free ions. Gyemant found that the increased conductivity due to an applied field only occurred in the direction of this field; the conductivity in a direction at right angles to the polarizing field was unchanged. Thus the number of free ions could not have been increased. The increase of conductivity may be due to inter-ionic forces, as already described, and in this case the difference between the d.c. and a.c. high-voltage results will be due to the fact that they are concerned with the motion of different ions. Gyemant suggests a process involving the formation of a chain of pairs of associated ions of opposite sign in the direction of the strong field and the passing of ions from one pair to the next, but the evidence in support of this suggestion is not as yet very strong.

It is doubtful whether certain features of the present results can be adequately accounted for on the basis of the theory of inter-ionic attraction, viz.

(*a*) The existence of a critical voltage gradient below which the a.c. conductance is to a very close approximation independent of the field, and above which it increases with the field;

(*b*) The effect of the thickness of the material on the increase of a.c. conductance with stress;

(*c*) The time effect observed with thin specimens.

These phenomena are not inconsistent with a theory of ionic collision, but the existing theories of cumulative ionization will not explain the form of the authors' curves for the increase of conductance with stress. Further work on this point is advisable.

Proposed Further Work.

It has been shown that the dielectric properties of cellulose acetate are complicated by the simultaneous operation of several molecular or ionic processes, each characterized by a definite time-constant. These time-constants could be determined by making observations of power factor over a very wide range of frequency and noting the points at which maxima occurred. This would constitute an important step towards the solution of the problem. Observations over the widest possible range of frequencies would be required, and it might be advisable to control the time-constants to some extent by taking the temperature of the sample over as large a range as possible.

In order to study further the molecular or ionic process it would be advisable to simplify matters as far as possible by working with materials of known composition. It is suggested that these should be obtained by taking pure liquids with neutral molecules, e.g. hexane or benzene, and adding to them various proportions of other materials known to possess polar molecules, or molecules which dissociate into free ions on solution. The properties of such materials in the solid and liquid state over a wide range of conditions, including those of the present investigation, may be expected to yield information as to the relative importance of the various processes and the properties peculiar to each of them.

A STATISTICAL EXAMINATION OF SPECIFICATIONS FOR THE MECHANICAL TESTING OF LINE INSULATORS*

By W. T. O'DEA, B.Sc.Tech., Associate Member.

(*Paper first received* 30*th October*, 1937, *and in final form* 1st *February*, 1938.)

SUMMARY

The application of statistical methods to an examination of the value of current specifications in determining the mechanical suitability of line insulators shows that unexpectedly great aberrations may occur. A detailed analysis of a Central Electricity Board specification, for instance, illustrates how appreciable are the chances of passing a batch containing a large number of defective units, and it may be argued that too much importance is attached to a test of doubtful value.

It may be possible to go some way towards reducing the discrepancy limits by adopting a more actuarial attitude towards the interpretation of results. Specification levels might be arrived at by the methods described in B.S.S. 600—1935, and a hypothetical case has been examined. In practice it would first be necessary to determine by research whether

(1) The frequency curve for line units was statistically determinate.

(2) Reliable specification levels could be determined.

It is also pointed out that samples of not less than 30–50 units should be tested, although these might be drawn from larger batches.

The final section of the paper contains the author's conclusions as to the value of mechanical consistency and a suggestion that resistance to thermal stresses might profitably receive more attention.

(1) INTRODUCTION

A standard specification should define the qualities required in a product and also stipulate tests to discover whether a product submitted from a possibly untried source will have substantially the qualities desired. What is therefore necessary is a semi-legal document so drafted that the maximum difficulty is placed in the path of non-compliance while the minimum burden is placed on the supplier of a product which is satisfactory. It is essential to make two basic suppositions:—

(1) A hypothetical manufacturer of completely unknown skill, experience, and integrity.

(2) A hypothetical inspector who has no prima facie knowledge of the range of variations of possibly well-tried commercial articles, or their normal service performance. Where inspectors or manufacturers are referred to in the paper they are presumed to be of these hypothetical types.

(2) AN EXAMINATION OF TESTING FOR GUARANTEED MINIMA

The usual methods of determining, by type tests, whether a batch of articles may be accepted as complying with a specification, are normally of such a hit-or-miss nature that the relatively few breakdowns experienced in service may be taken, not as a testimonial to careful inspection, but as a compliment to the general level of skill of manufacturers. As an example we may take the testing of porcelain line-insulators for mechanical suitability, and as a typical specification examine that employed by the Central Electricity Board, a body which has probably had a profound influence on current practices, in this country at least. This specification goes farther than B.S.S. No. 137, which is applied to many less extensive contracts.

The following extracts are taken from Specification C.E.—P.L.I. and refer to the mechanical requirements demanded in the case of cap-and-pin type insulators which were assembled into strings of 9 units for 132-kV service. The maximum (theoretical) working load was 4,000 lb.

" *Routine Tests.*

" (*a*) *Insulator Routine Mechanical Test.*—The insulator unit shall be arranged complete as in service, and a load 25 per cent in excess of the maximum working load stated in Schedule D shall be applied to the insulator. The load shall be maintained for one minute without injuring or loosening the insulator or fittings.

" *Type Tests.*

" The following type tests, with the exception of the voltage distribution test (*f*), shall be carried out in the order given on two insulator strings selected by the engineers at random from each batch of not more than 300 insulator strings submitted, the individual units having already passed the routine tests.

" Before selection of the sample insulator strings the contractor shall indicate clearly to the engineers the actual insulators and their number constituting the batch submitted.

" In the event of a sample from any batch failing to pass any one of the type tests, a further four complete insulator strings shall be selected by the engineers from the same batch and shall be submitted to such of the type tests as may be required by the engineers.

" In the event of failure occurring in any of these additional tests the whole batch shall be rejected, but if no such failure takes place the batch may at the discretion of the engineers be passed as satisfactory.

" Where a batch of insulators has been rejected the contractor shall satisfy the engineers that adequate steps will be taken to mark or segregate the insulators constituting the batch in such a way that there shall be no

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

possibility of the rejected insulators subsequently being re-submitted for test or supplied for the Board's use.

. . . . .

"(h) *Mechanical Type Tests to Destruction.*—Each insulator unit of one of the selected strings complete with fittings as in service shall withstand for one minute without damage, permanent distortion, or loosening of fittings, a load 2·5 times the maximum working load specified in Schedule D. It shall subsequently be tested to destruction, and the failure shall not take place at a figure less than the breaking load stated in Schedule D.

"(k) *Electro-mechanical Type Test.*—Each insulator unit of one of the selected strings shall be tested for one minute to $2\frac{1}{2}$ times the maximum working load stated in Schedule D, and simultaneously a voltage of not less than 75 per cent of the dry flash-over voltage shall be maintained between its terminals throughout the test. An insulator unit shall be considered to have failed under the electro-mechanical test when breakage takes place or when a puncture occurs in any part of it or when a discharge of any sort passes from one terminal to the other."

It will be seen immediately from the above that:

(1) Any insulator failing mechanically at 5 000 lb. or less is excluded from the type tests.

(2) Out of each batch of not more than $300 \times 9 = 2\,700$ insulator units, $2 \times 9 = 18$ are type-tested to destruction, or to the electro-mechanical test load of 10 000 lb.

In many branches of industry, within the author's personal knowledge, it is not uncommon to submit batches of material to tests at least as rigorous as those specified *before* the inspector arrives. This practice is particularly common in the case of switchgear, for instance, and saves wearisome and pointless delays due to easily remediable minor faults which may be cleared by more or less simple adjustments. There can be no guarantee that the same practice is not resorted to in the case of insulators, and there is no conclusive evidence that the residue of a batch of insulators previously submitted to a routine test of, say, 9 000 lb. (or even 10 000 lb.) will behave any differently when later subjected to 10 000 lb. in the presence of an inspector. The manufacturer need not disclose the results of such tests; there is nothing to indicate that they have been taken; and a number of defective units which might have led to the rejection of the batch may have been eliminated in the process.

Presumably the 5 000-lb. routine test figure has been kept low to prevent the unnecessary straining of units which are later to be put into service. If so it presupposes that the manufacturers will not have chanced the so-far doubtful effect of increasing this figure in the belief that by so doing they may have made it easier for their insulators to pass the type test.

It may be pointed out that the latter requires each unit to withstand 10 000 lb. for one minute "*without damage, permanent distortion, or loosening of fittings.*" Why, then, if 10 000 lb. has no deleterious effect, reduce the routine test to 5 000 lb.?

If, out of the 18 type-tested units, none should fail, the batch is accepted. If only one should fail a further $4 \times 9 = 36$ units are selected and put through the same tests. If all 36 pass, the batch is then accepted at the discretion of the engineers, in spite of the fact that one of the first 18 was unsuccessful. The idea, obviously, is to make allowances for the possibility of a single erratic result which may have been due to bad luck. (The specification does not clearly limit the initial failures to 1, but it is assumed that this is the limit of the engineers' discretion.)

Let us examine this test statistically. Suppose, in the 2 700 insulators, there are actually n units which would fail on test if they were tested by the inspector. If all 2 700 units were tested to destruction—or to 10 000 lb.—n would prove faulty. As we want to have units to put on the line we can only afford to test 18 out of the 2 700 to destruction. Also, as we do not fully believe the words of the specification, we imagine that we might do some damage if we routine-tested all the units to 10 000 lb. We want the fact that there are n faulty ones in 2 700 to be shown by results on the 18 we test (unless we are manufacturers, in which case we have reason to hope that none of the 18 will prove faulty and that the n, if present, will be placed in quiet suspension positions where nothing more may be heard of them).

Now the number of ways in which 18 units may be chosen out of 2 700 units is:

$$_{2\,700}C_{18}$$

The number of *good* units is $(2\,700 - n)$, and the number of ways we can choose 18 *good* units is

$$_{(2\,700-n)}C_{18}$$

The probability that the 18 insulators chosen will contain no defective units is therefore

$$\frac{_{(2\,700-n)}C_{18}}{_{2\,700}C_{18}} \times 100\,\% \quad . \quad . \quad . \quad . \quad (1)$$

Values of this term may be plotted against various values of n, as shown in curve A, Fig. 1.

We are now aware of the fact that if there should be only one defective insulator in the whole batch of 2 700 there is one chance in 150 that it will be chosen for test, thereby spoiling the 100 % record of the batch. From curve A it will be seen that there is the same chance of a batch containing about 700 defective insulators passing without question. We cannot avoid taking the chance of accepting the very faulty batch, but it seems a pity not to give a second chance to the good batch which would otherwise be rejected. Therefore, in the event of one of the 18 insulators proving defective we take a further batch of 36 and hope to get no more failures.

The first batch already tested, under these latter conditions, must have contained 17 good insulators and 1 bad insulator (as if it contained more than 1 bad unit the engineers would presumably have rejected it out of hand). The number of ways in which such a choice may be made is

$$_nC_1\ _{(2\,700-n)}C_{17} = n \cdot {}_{(2\,700-n)}C_{17} \quad \text{ways,}$$

which is equivalent to

$$\frac{n \cdot {}_{2\,700-n}C_{17}}{_{2\,700}C_{18}} \times 100\,\% \quad . \quad . \quad . \quad . \quad (2)$$

of the total number of ways of choosing 18 insulators. 36 insulators out of the remaining 2 682 containing $(n-1)$ defective specimens must all be found to be satisfactory. The probability of this happening is

$$\frac{[2\,682-(n-1)]C_{36}}{2\,682C_{36}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

If n is small most of the first tests will be successful, but even those batches which do not pass immediately should rarely contain more than 1 defective insulator, so that a second test may be called for in the case of most of the few unsatisfactory first tests. The second test, in these cases, will frequently be successful.

If $n = 100$ about 37 % of samples will contain 17 good

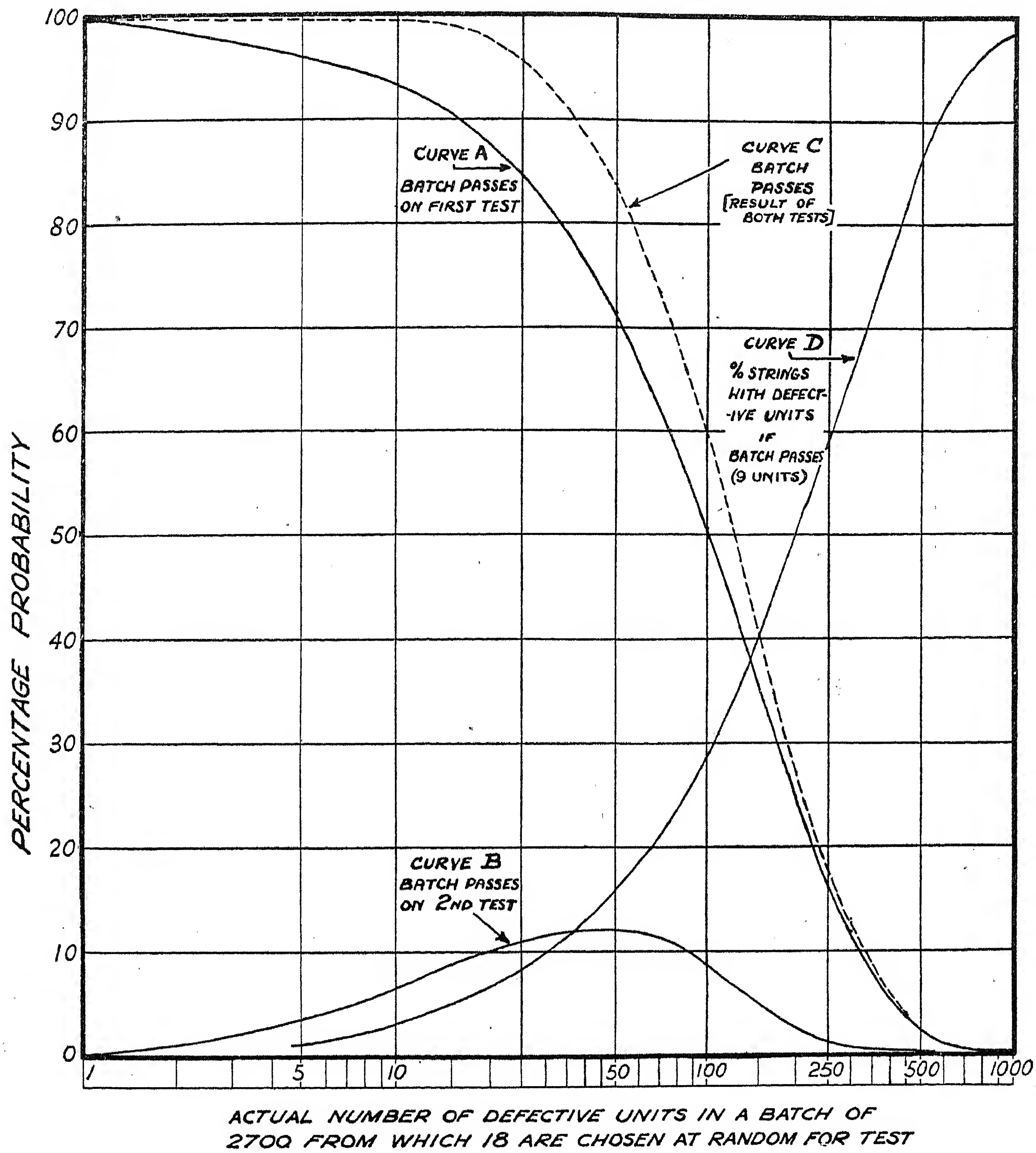

Fig. 1

and the probability (per cent) of a batch passing right through on a second test is

$$100n\frac{(2\,700-n)C_{17}}{2\,700C_{18}}\cdot\frac{[2\,682-(n-1)]C_{36}}{2\,682C_{36}} \quad . \quad . \quad (4)$$

This expression may be calculated for various values of n, and a sufficiently close approximation [assuming term (3) to be $\left\{(2\,664-n)/2\,664\right\}^{36}$] is plotted in curve B, Fig. 1.

The shape of this curve is what might be expected in view of the following observations.

and only 1 bad unit; 50 % will contain no bad units and 13 % more than one. Of the 37 % submitted to a second test quite a reasonable proportion—actually about 1 in 4—should contain no defective units. When $n = 50$, however, although only about 24 % are submitted to a second test, about 50 % of the batches of 36 samples submitted will contain no defective units. When $n = 500$ only 6 % of the sample batches contain 1 bad unit and over 91 % will contain 2 or more bad units which preclude the batch from a second test. Even if there were a second test it would be about 99 % unsuccessful.

Curve B, added to curve A, produces curve C, which

shows the percentage of batches which should be passed as a result of the first test or both tests together.

As a matter of interest a further curve has been added to Fig. 1. Let there be n defective insulators in a batch which has passed on test. These insulators are to be made up into strings and placed in service.

$$\frac{\text{No. of ways of choosing 9 good insulators}}{\text{No. of ways of choosing 9 insulators}} = \frac{{}_{(2\,682-n)}C_9}{{}_{2\,682}C_9}$$

passing, and should this happen the units will pass into service. In such an event it is probable that 1 string in 2·5 will begin its career mechanically unsound.

Curve D might be interpreted in another way. If the batches submitted to the inspector consistently contain 150 defective units, only 1 batch in 3 will pass. The units on the line, however, will be entirely made up from batches containing 150 *undetected* defective units, and the percentage of defective strings will be 40. The author

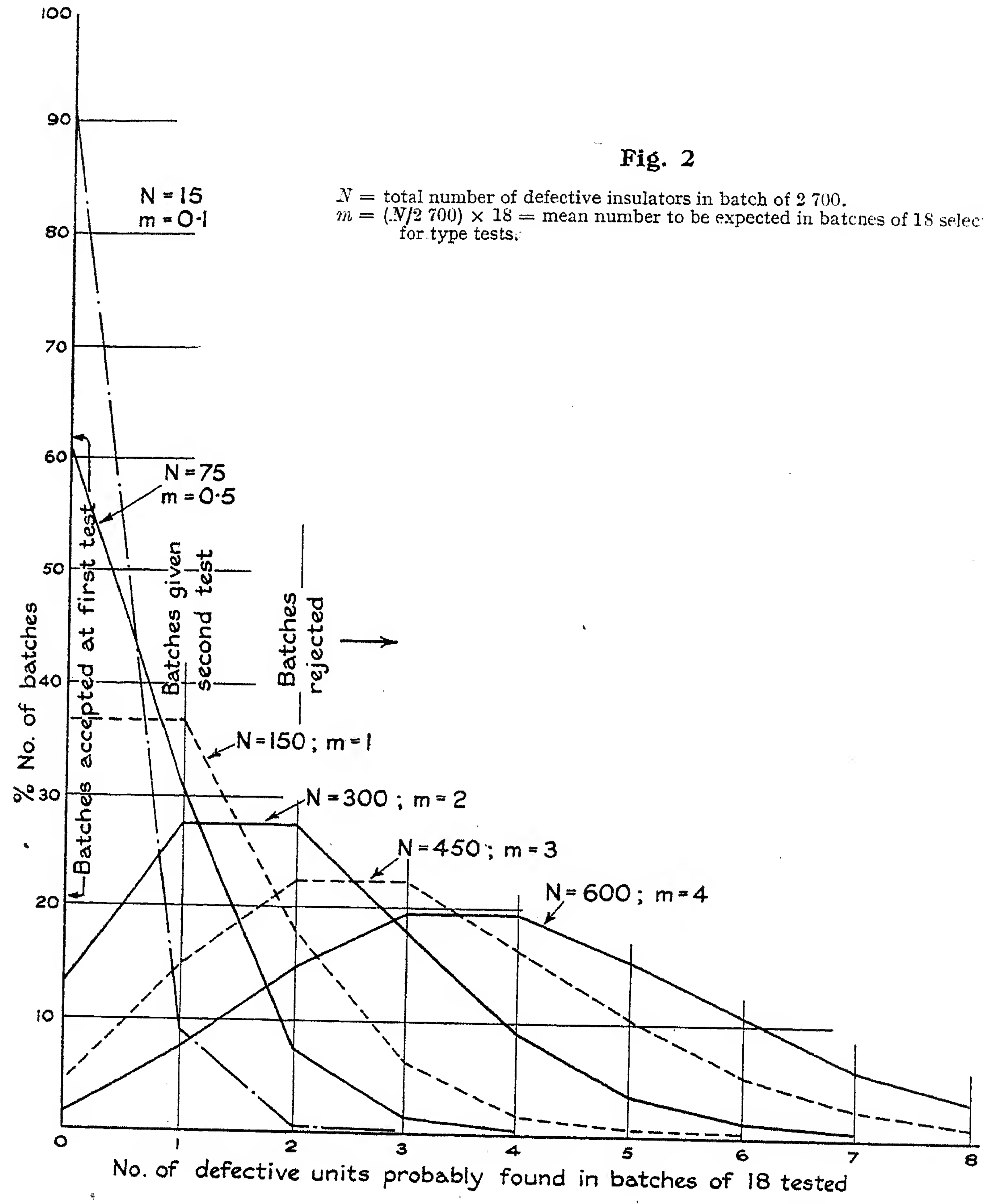

Fig. 2

N = total number of defective insulators in batch of 2 700.
$m = (N/2\,700) \times 18$ = mean number to be expected in batches of 18 selected for type tests.

ignoring the complication of having possibly destroyed a further 36 insulators on a second test.

$$\left.\begin{array}{l}\text{Probable number of insu-}\\ \text{lator strings contain-}\\ \text{ing 1 or more defective}\\ \text{units}\end{array}\right\} = 298\left(1 - \frac{{}_{(2\,682-)n}C_9}{{}_{2\,682}C_9}\right) \quad . \quad (5)$$

This figure, for various values of n, is expressed as a percentage in curve D, Fig. 1.

Supposing only one batch of insulators was up for test and that, unknown to anybody, it actually contained 150 faulty units. It is about a 1 in 3 chance of its

would hesitate to accept this purely theoretical interpretation as it is difficult to conceive an authority accepting 1 batch in 3 out of a large number of batches, or the manufacturer who could stand the economic strain of having 2 batches in 3 consistently rejected. There is, however, more reason to accept this reasoning as applicable to the earlier portion of the curve where $n = 25$, say, and the proportion of defective strings is 8 %. Most engineers and most manufacturers would not be unduly disturbed by a 4 % rejection of batches. The figures of 4 % and 8 % quoted would in practice be subject to fairly wide variations, depending on the

number of batches considered as a whole and on the way an average of 25 defective units per batch was distributed among them. As we cannot know exactly how many defective units there are unless we test every one up to the guaranteed minimum load, we can say, from the above reasoning, that if 10 % of the strings contain one or more defective units in service we should not be very surprised. The case of tension sets made up of two strings in parallel is considered in Appendix (3).

By " defective unit " we mean any which will not stand up to the guaranteed minimum breaking load. We do not mean one that is necessarily going to fail. There is, even in tensioning positions, a factor of safety of something less than 2·5 which we hope will take care of that contingency. In service, however, we may expect loads to be partly live loads, and if the theoretical maximum working load is ever reached under such conditions a factor of safety of the full 2·5 does not appear to be excessive. Fortunately we may reasonably expect far more of the " defective " units to have a tensile strength close to 10 000 lb. than close to the routine test load of 5 000 lb. unless we have had the very bad luck to pass an extremely poor batch.

These are consoling thoughts. The fact remains that this test may tell us something very substantially different from what we are hoping to discover by it.

The probabilities of Fig. 1 may also be constructed in a different way to give an equally illuminating set of curves. If there are n defective units in a batch of 2 700 the mean number of defective units to be expected in the sample of 18 selected for test is $18n/2\,700 = n/150$. Now if $n = 150$ units we should therefore expect, on an average, 1 defective unit in each 18. The probable variation from the mean, is however, given by the Poisson exponential expansion of $e^{-m}m^x/x!$, which will be found tabulated in Pearson's " Tables for Statisticians and Biometricians " (Part I). These values are plotted in Fig. 2, and although the points are joined by lines to discriminate between the various curves the values are actually discrete. The values taken from the ordinate 0 and replotted against values of n give approximately curve A, Fig. 1. The same procedure at ordinate 1 gives a curve showing the percentage of batches which would receive a second test (but does not indicate how many would pass, as shown in Curve B, Fig. 1). The other ordinates give successive values of rejects where 2 or more insulators are found defective in the first 18.

If 2 defective insulators are found we do not know whether we have alighted upon the 15 % probability of $n = 600$, or the 18 % probability of $n = 150$, or the 8 % probability of $n = 75$, or the 22 % probability that $n = 450$, or the $\frac{1}{2}$ % probability that n is only 15. By chance we may have alighted on or near the 27 % probability of the number of defectives being proportional to the relative number in the batch.

In 40 % of cases, where n ought to be 2, however, the batch would either be passed or get a second chance owing to 2 defectives not being drawn, as against the 33 % of cases in which more than 2 would be drawn and the batch would still be rejected—though on weightier grounds than are actually justifiable.

We see, then, from these various probability curves, that the gamble on a small random selection of samples proving the worth of the batch may fail more often than is comfortable. Also, if the specification requirements (clause h) are to be relied upon there is no reason why we should ever find a defective insulator if the manufacturer has made a practice (whether it be ethical or not) of giving a really strong tug at every pin before the inspector arrives, and throwing out all those units which might later give trouble on test. Such conduct would make the gamble even more unreliable. We will now examine a method by which we may hope to circumvent such disturbing conduct to a certain extent. It may be regrettable that we have to envisage such reprehensible practices (that is, from the inspectors' and consultants' point of view), but if we can trust the products of all manufacturers (as a body, not as individuals) why send inspectors out at all?

(3) A STATISTICAL EXAMINATION OF TEST RESULTS

Section 7 of B.S.S. 600—1935, compiled by Dr. E. S. Pearson, describes a statistical process which might well be adapted to the case of line-insulator units. Before it is possible to state definitely that the method is superior to that of guaranteed minimum testing, a large number of units should be tested to destruction to discover whether the results lie on a statistically determinate curve and, if so, what form the curve takes. It seems highly probable that a statistical relationship would be discovered, but whether it would be of the normal form* or some other form for which certain corrections would be necessary in the following processes is a matter which can only be decided by research, for which the author has no facilities. For the purpose of illustrating the principles involved it has been assumed that the mechanical strengths of line insulator units from a large batch, plotted against frequency of occurrence, will give a normal curve of the general type:—

$$y = \frac{1}{\sigma\sqrt{(2\pi)}}e^{-(x-\bar{X})^2/(2\sigma^2)}$$

where $\bar{X}$ is the *mean* and σ the *standard deviation*.†

Fig. 3 shows two hypothetical curves of this type, the mean in each case being 13 000 lb. and the area of each curve also being the same. The equal areas mean that each curve has been determined as the result of an equal number of observations. Curve XA′H, however, corresponds to a batch of units of which 10 out of every 2 700 are defective by guaranteed minimum standards, while curve XA″H corresponds to a batch containing 100 defective units out of every 2 700. That is to say,

$$\frac{\text{Area XGG}'}{\text{Area XA}'\text{H}} = \frac{10}{2\,700}$$

and

$$\frac{\text{Area XGG}''}{\text{Area XA}''\text{H}} = \frac{100}{2\,700}$$

The guaranteed minimum is represented by the point G (= 10 000 lb.). From curve C, Fig. 1, it will be seen

* The coins tested by Prince and Whitehead (see *Journal I.E.E.*, vol. 81, p. 515) had characteristics which followed substantially the normal-frequency type of curve.

† B.S.S. 600 gives the following definitions:—
Mean.—The sum of the observations divided by their number.
Standard deviation.—The square root of the mean of the squares of the deviations of all the observations.

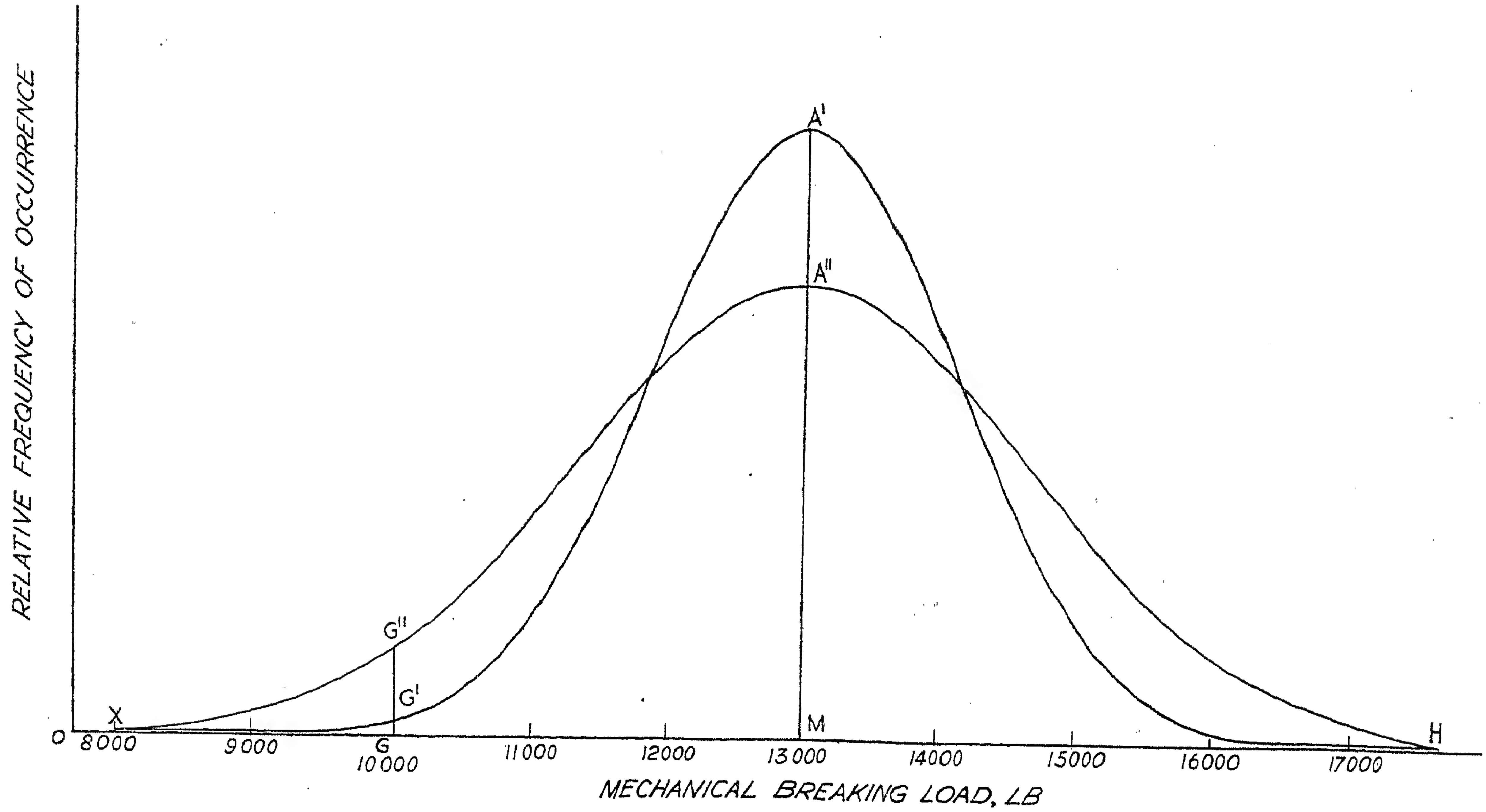

Fig. 3.—Normal frequency curves.

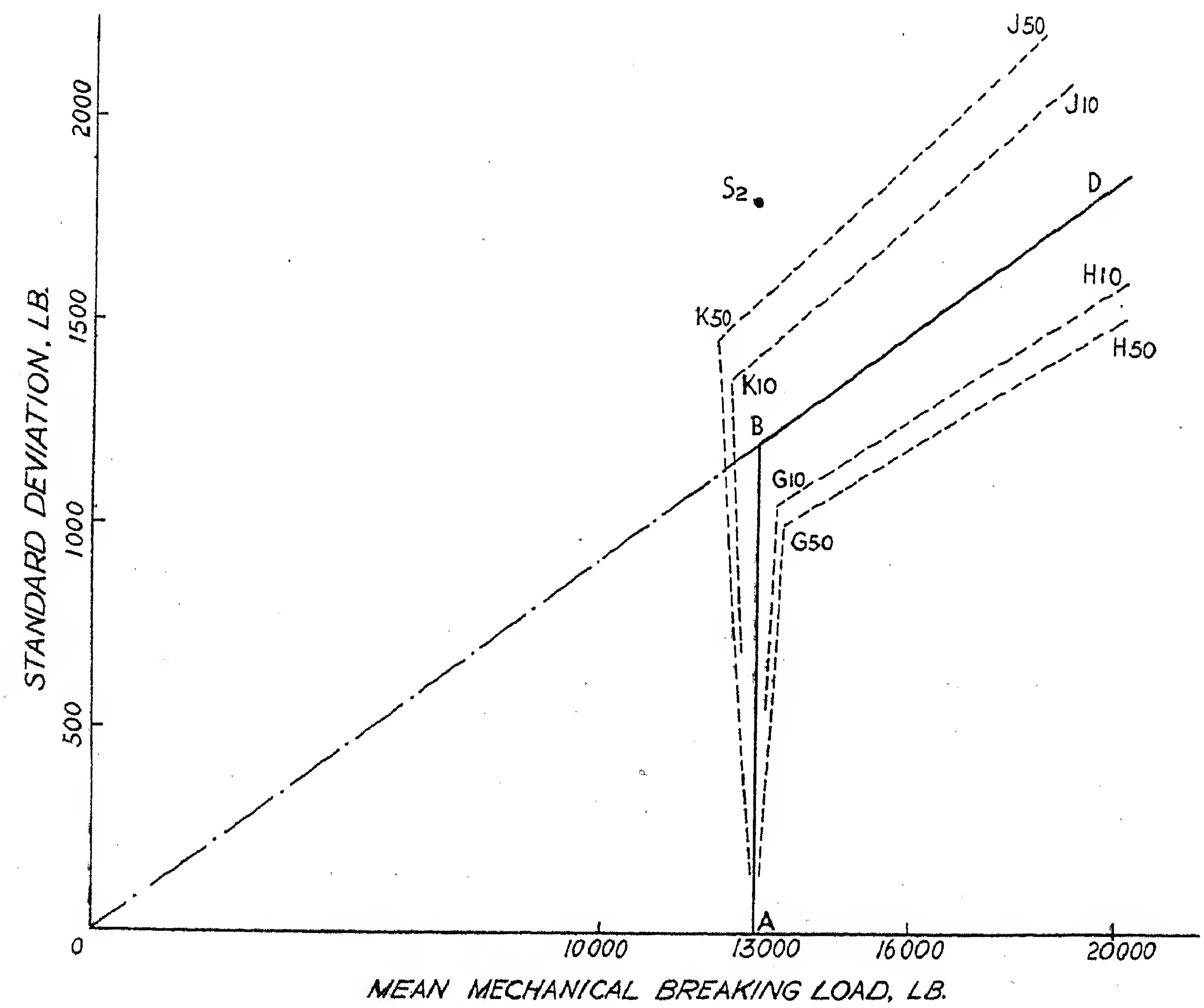

Fig. 4.—Specification levels for statistical test.

that, by guaranteed minimum standards, there is a 99·5 % probability of accepting a batch to curve XA′H and a 60 % probability of accepting a batch to curve XA″H.

Now if we work out standard deviations for these two curves we get, for XA′H, $\sigma = 1\,200$ lb. and for XA″H, $\sigma = 1\,800$ lb. Suppose that we decide that a mean of 13 000 lb. and a standard deviation of 1 200 lb. is a desirable specification level. If, on testing a batch, we get a higher mean it is plainly fair to allow a higher standard deviation. We may thus construct a curve as in Fig. 4, in which the line AB, BD represents the nominal acceptance line. If we test sufficiently large numbers of units and the result falls to the right of AB and below BD we may say that the units would satisfy the specification. It so happens, however, that we can only test a rather small number of units in the hope that the results therefrom will be representative of the characteristics of the whole large batch. We may therefore reject a substantial number of worthy batches if we adhere rigidly to the line ABBD. Fortunately we can construct another line which may enable us to allow for the variations in small sample characteristics as compared with large batch characteristics and yet limit the number of undesirable batches which will be by chance accepted as a result.

B.S.S. 600 gives formulae and tables of what are known as "fiducial limits." Before proceeding further it may be stated that it becomes apparent that the number of units in the test sample should be increased from 18 to 30, or preferably 50. The development of Fig. 4 has been made on the assumption that the test sample is 50 units, but there seems no valid reason why the number of units in a batch should not be raised to the compensatory figure of, say, 5 000. The following observations are, however, based on a batch size of 2 700 units.

It is quite a simple matter to construct lines $AK_{10}, K_{10}J_{10}$ and $AG_{10}, G_{10}H_{10}$ so placed that we may say that there is only 1 chance in 10 that results from a small sample taken from a large batch from which the results would lie on the line AB,BD would fall outside the area bounded by these lines. Moreover there is only a 1 in 20 chance that the result will be to the left of AK_{10} or above $K_{10}J_{10}$. Similarly the lines $AK_{50}, K_{50}J_{50}$ and $AG_{50}, G_{50}H_{50}$ confine an area in which the sample result will fall 49 times out of 50. Only once in 100 times will the result be to the left of AK_{50} or above $K_{50}J_{50}$. It so happens in this hypothetical case that the 1 in 10 lower limit line (sample results better than the characteristics of the batch from which the sample is taken) corresponding to curve XA″H (where $\overline{X} = 13\,000$ and $\sigma = 1\,800$) is practically coincident with the line $K_{50}J_{50}$. Therefore we may say, in this case, that taking the line $AK_{50}, K_{50}J_{50}$ as the specification acceptance level there is a 1 in 100 chance of a batch of 2 700 units containing 10 defective units being rejected and a 1 in 20 chance of a similar-sized batch containing 100 defective units being accepted. There is an even chance of acceptance where the batch (not sample) characteristics actually fall on the line $AK_{50}, K_{50}J_{50}$, i.e. where there are 54 defective units in 2 700. (The term "defective unit" means one defective by guaranteed minimum standards.)

If, on batches rejected at the first test, we allow a second similar test for acceptance the above chances become:—

Number of defectives	*Chance of acceptance*
10	Practically certain
100	Less than 10 %
54	75 %

Although it may at first sight appear that these chances are no great improvement on those for guaranteed minima where the sample is 50 units (see curves F and H in Fig. 8), it should be remembered that they are very much more likely to remain substantially unaffected by any prior testing. If, therefore, by research we can obtain evidence that—

(1) Variations in the strength of line units are statistically determinate so that the above processes, possibly with corrections, may be applied to the results obtained;

(2) Reliable deviates may be specified;

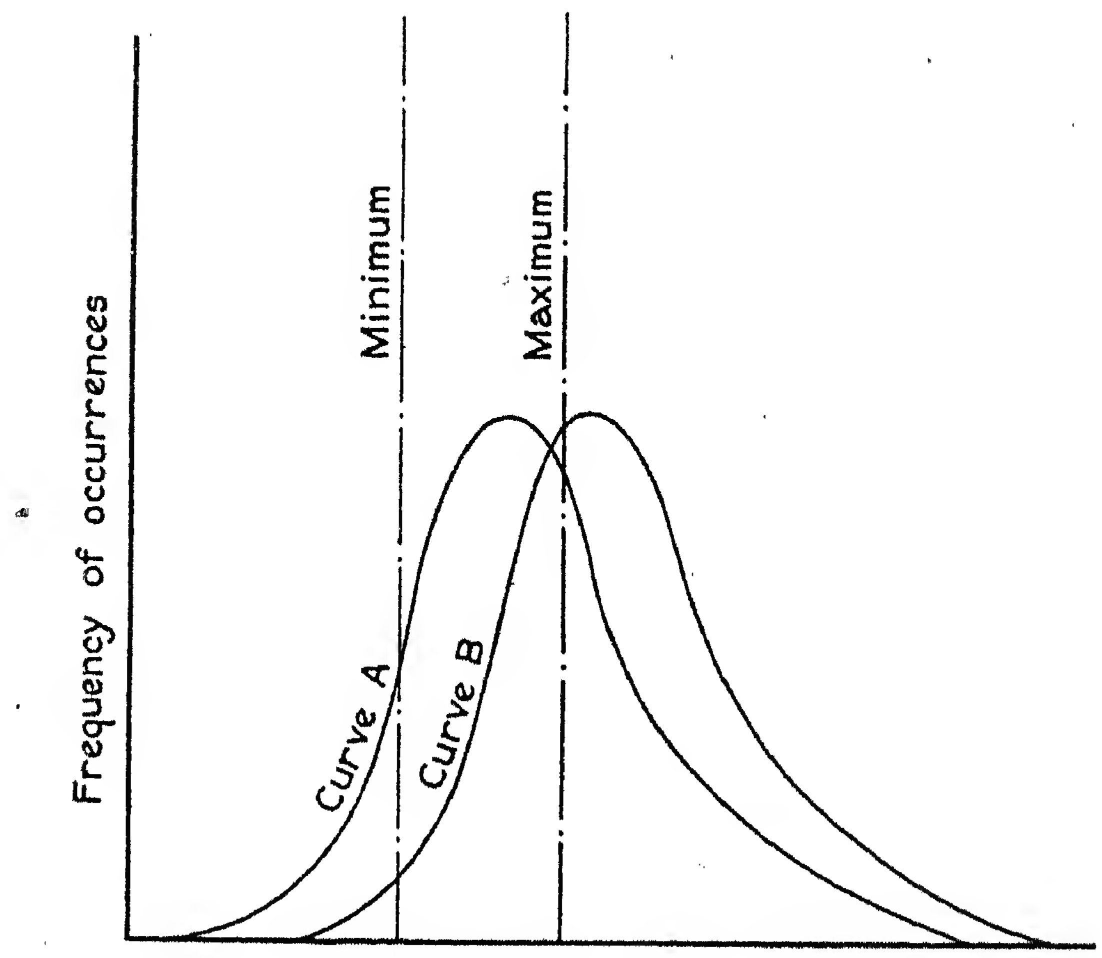

Fig. 5

we should have gained a far more reliable instrument than the guaranteed minimum on which to base acceptance or rejection of batches. When it is considered that the value of a large batch of units may be of the order of £2 000 the extra complication is negligible.

(4) "PER CENT AVERAGE VARIATION"

The A.I.E.E. standards (clause 41.203) specify for puncture tests a "per cent average variation" which shall not exceed 10 %. This is a simple test of consistency which might be adapted to the mechanical test also. The standard error in the arithmetic mean of N observations is $\sigma/\sqrt{N}$, where σ is the standard deviation. In the A.I.E.E. tests N may be as low as 3, but there is a saving clause which allows at least a further 10 tests at the discretion of the manufacturer. For a normal-frequency curve the mean (or average) deviation is simply $0{\cdot}8 \times$ (standard deviation). If the curve for line insulators is found not to follow the exact normal form the standard deviation may provide a better test of consistency, and the procedure of the preceding Section may very probably be found to be better still.

It is difficult to find a valid reason why the A.I.E.E. test specifies that in the event of a further 2 % (or 10 insulators) being tested the results of the first tests shall be ignored. The greater the value of N, the greater the probable accuracy, statistically speaking. This type of test, although only partially satisfactory, is better than a straightforward minimum proving.

(5) MAXIMUM AND MINIMUM LIMITS

In October, 1929, the V.D.E. issued a set of standards for various types of insulator, and the proof load was given in the form of minimum and maximum values for cap-and-pin type insulators. While, if consistency is a virtue, this appears to be a praiseworthy matter, it will be seen from Fig. 5 that it may have the effect of invalidating a greater number of batches which would fulfil the frequency curve B than those fulfilling frequency curve A, although curve B is equally consistent, but the units are stronger on average.

It would appear, therefore, that a statistical method of test is better.

(6) CONCLUSIONS

It appears to be established that very wide variations in quality may be expected in batches of insulators either accepted or rejected by means of mechanical type tests of the kind specified in the Central Electricity Board and other standard specifications. There is, however, much to be said for consistency in results, as illustrated by curve XA′H (Fig. 3), which would generally be admitted to be superior to curve XA″H.

Some measure of the consistency of a batch may be obtained (within fairly wide experimental limits, it is true) from consideration of the mean and standard deviation obtained by tests on a sample. These factors may be determined with increasing confidence in their accuracy as the number of sample units tested is increased.

It should be possible, as the result of fairly extensive researches for which the author has unfortunately no facilities, to determine permissible specification levels for line insulators of the usual types.

The manufacturer would still be able, by prior testing, to evade a number of unfavourable results, and the only way of circumventing these practices would be to test all units up to their guaranteed minimum load and reject all that do not succeed before commencing the type tests for mean and standard deviation (which might be modified accordingly).

If this were done we should have eliminated *all* units which might fail at a load below a specified amount, and we must therefore examine the position to see whether there is any virtue in demanding consistency in the remainder.

WHAT IS THE VALUE OF CONSISTENCY?

The author's remarks hitherto have been confined to a mathematical interpretation of various methods of test. The following comments are conjectural and consist of his personal interpretation of this investigation on a broader basis. Much research, for which he has not the facilities, would be required before such conjectures could be definitely substantiated, modified, or disproved.

We have seen that current specifications appear to put a premium on consistency in mechanical test values, as there appears to be some reluctance to test all units up to the guaranteed minimum breaking load and simply weed out those which fail. The author is of the opinion that this is an inefficient way of saying that we want consistency because thereby we shall get a better batch of insulators for service conditions—probably because higher thermal resistance may be expected from a batch which is mechanically subject to only small variations in tensile strength. Experience of a large number of test results on various designs of unit appeared to bear out this latter expectation.

On the other hand a batch of units which gave a wide range of mechanical test values, the average of which was correspondingly high, might be expected to pass current specification tests although its thermal resistance might be relatively poor.

Therefore, unless there is some other reasoning which is too inscrutable for immediate comprehension, one would be led to deduce that the present specification thermal tests are not severe enough [assuming that clause (h) in the C.E.B. specification quoted may be honestly fulfilled].

The thermal stresses which a line unit may have to resist in service are very high. A complex fabrication made up of galvanized iron, cement, porcelain, cement, and galvanized iron, in layers may have one side exposed to a sun temperature of, say, 130° F. while the other side is in the shade at the ambient air temperature of 80° F. A summer hailstorm may then bombard the whole structure with a mixture of ice and water. This, and other lesser thermal stresses, are far from uncommon during the life of a unit in service, while the thermal effect of a flashover followed by a thunderstorm deluge is still very imperfectly understood. The unit must also be able to withstand a succession of live mechanical loads due to conductor tension accompanied by vibration. Unfortunately, even in the manufacture of the porcelain shell alone, we have to compromise between its ability to withstand these two sets of service conditions, as will be seen from Fig. 6 which is taken from a paper by H. Handrek ("Porzellan als Werkstoff," *Zeitschrift des Vereines Deutscher Ingenieure*, 1927, vol. 71, p. 1553).

If we determine upon a compromise and make units of various sizes from the same porcelain body we find (from an examination of various manufacturers' designs) that while, in order to get 10 000 lb. guaranteed minimum electro-mechanical test value out of a normal 10-in. disc it is necessary to introduce complication into the pin contour, when 20 000 lb. or more is required it is usual to revert to a simple design of pin. This is very largely due to the fact that the depth of insertion into the cemented cavity must be increased, and if the complicated contours of the 10 000-lb. pin are employed (in scaled-up form) under these conditions the thermal performance of the unit will be unsatisfactory.

This simply means that 10 000 lb. is a figure which is forced out of the normal 10-in. disc at 5 in. to $5\frac{1}{2}$ in. centres at the expense of thermal resistance, but as even under these conditions the units will pass current specification temperature-cycle tests it would not be economical for any one manufacturer to obtain the 10 000 lb.

by introducing a better and simpler unit, as in order to do so it would be necessary to increase the size and therefore the cost.

Now if the minimum criterion for mechanical acceptance on test were altered to a mean value of at least so much, combined with a standard deviation not greater than some amount determined after investigation, it would not be economical for a manufacturer to try to force additional mechanical strength out of a unit, as by so doing he would imperil his standard deviation figures. The same result, however, might possibly be obtained with equal success by making the temperature-cycle test more severe, the two factors being interdependent.

In case this reasoning might appear to be unsupported by facts, it may be remembered that the strength of a 10-in. cap-and-pin unit at 5-in. centres some 15 years ago was very commonly quoted as "10 000 lb. average." Since then the guaranteed minimum has been insisted upon and the figure is still 10 000 lb. Fig. 6 shows that

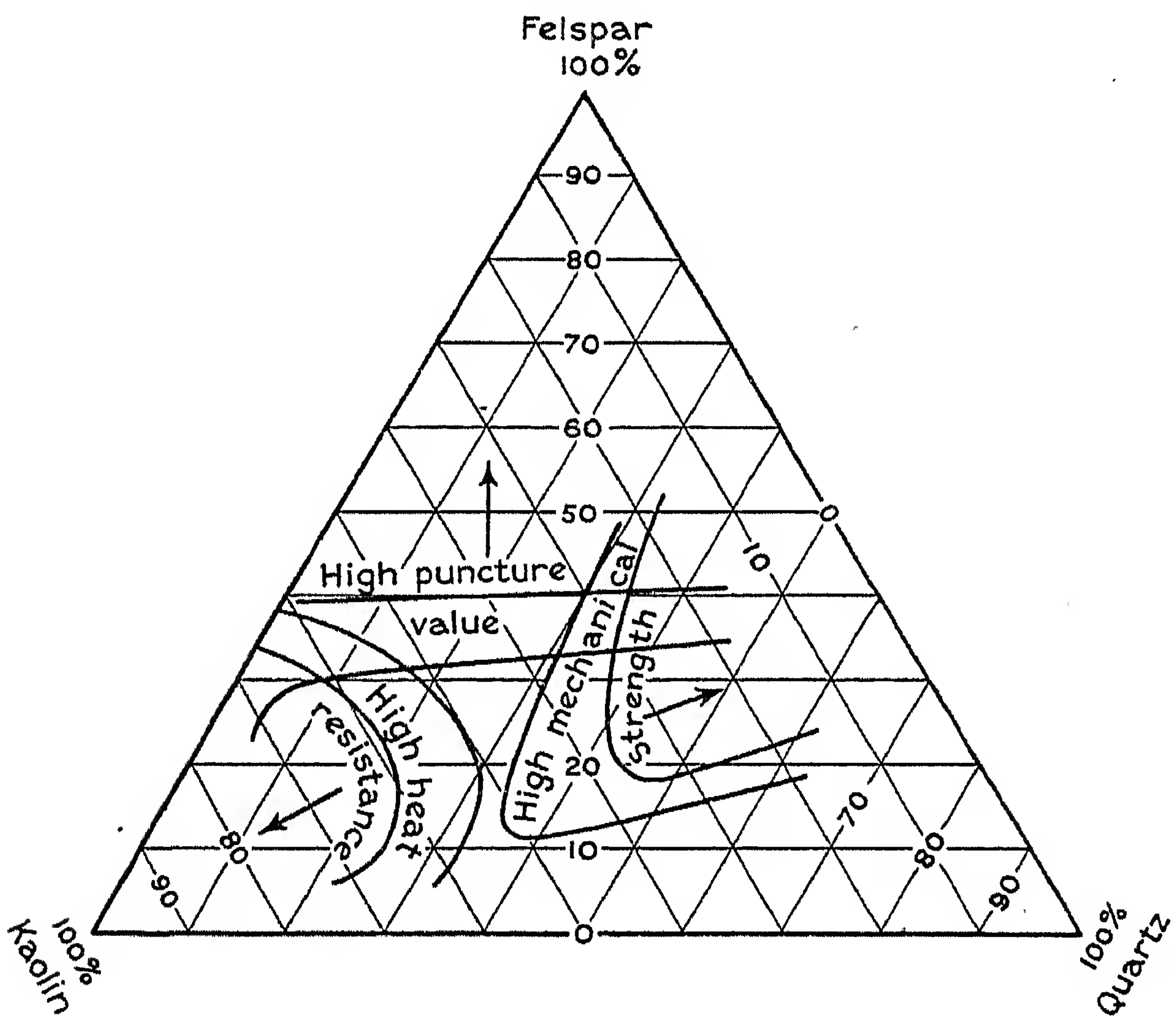

Fig. 6.—Effect of composition of porcelain body on various characteristics.

The arrows show the direction of increase in the values of the characteristic described.

this may be obtained at the expense of thermal resistance. Puncture values have also increased, thereby accentuating this effect. Thermal resistance, however, has been restored to some extent by the now common expedients of coating the pin with a resilient medium and employing the sanded surface as a bond for the cement-porcelain joint. The shape and dimensions of the units remain substantially the same. Necessity has led to the general adoption of artifices to increase the resistance to thermal stress of units which would otherwise have failed to pass on test. In the author's opinion there has been too much concentration on mechanical and puncture test improvements which have been developed at the expense of all-round improvements now possible compared with 15 years ago. The result is a unit which is not as good as it might be for service.

It will be noted that the mathematical reasoning of this paper is equally attributable to puncture-voltage type-testing, but not very clearly to such characteristics as flashover, which depend largely on external characteristics that do not come under the heading of random variations as between units.

BIBLIOGRAPHY

G. I. Gavett: "First Course in Statistical Method" (McGraw-Hill, 1925).

L. H. C. Tippett: "The Methods of Statistics" (Williams & Norgate, 1931).

Karl Pearson: "Tables for Statisticians and Biometricians," Part I (Cambridge University Press, 1924).

E. S. Pearson: "The Application of Statistical Methods to Industrial Standardisation and Quality Control" (B.S.S. 600—1935).

APPENDIX 1

Fig. 7 is an extension of curve A, Fig. 1, to show the effect of altering the number of units chosen at random for guaranteed minimum type testing. It will be seen that the effect of choosing only 9 out of 1 350 instead of 18 out of 2 700 is almost negligible as far as the shape of curve is concerned—but the effect of 100 faulty insulators out of 1 350 is, of course, much worse than that of 100 out of 2 700. Conversely, it would be expected (and calculation shows) that the shape of the curve would alter very little if 36 insulators were tested out of a batch of 5 400. The effect of 100 faulty insulators out of 5 400 would not be as bad as that of 100 faulty out of 2 700, but against this must be placed the added seriousness of the rejection (by bad luck only) of a batch of as many as 5 400, and also the unwieldiness of such a batch which is more likely to be affected by variations in manufacture, firing, etc., which could not be properly described as random variations within the batch. Such variations should be made, as far as possible, random variations as between batches, a condition which favours smaller batches. The equation of these factors is not within the immediate scope of this paper.

Other curves show the effect of testing numbers greater than 18 units out of a batch of 2 700. The curves, as might be expected, became in effect steeper as the abscissae are on a logarithmic scale and the inspector, if confronted by 5 batches of which only 1 passed, should be much less uneasy in accepting the successful batch if he had tested 36 insulators in each, as he might expect only half as many units to be defective on average. In other words we may say that if T is the number selected for test per batch and x % batches are accepted as a result of the tests, the probability is that the average number of defective units in the batches accepted is approximately $18n/T$, where n is the number corresponding to x % in curve A, Fig. 1. (This approximation must be used with caution as it only holds if the number of units in the batch is very large compared with both n and T.)

Fig. 8 shows that it is possible, by choosing suitable sample numbers, to shift the probability curve so that there is relatively little chance of finding the steeply rising portion of curve D, Fig. 1. In other words we can reduce very materially the chance of putting into service a high percentage of strings containing defective units. The difference between curve C and curve H is very noticeable,

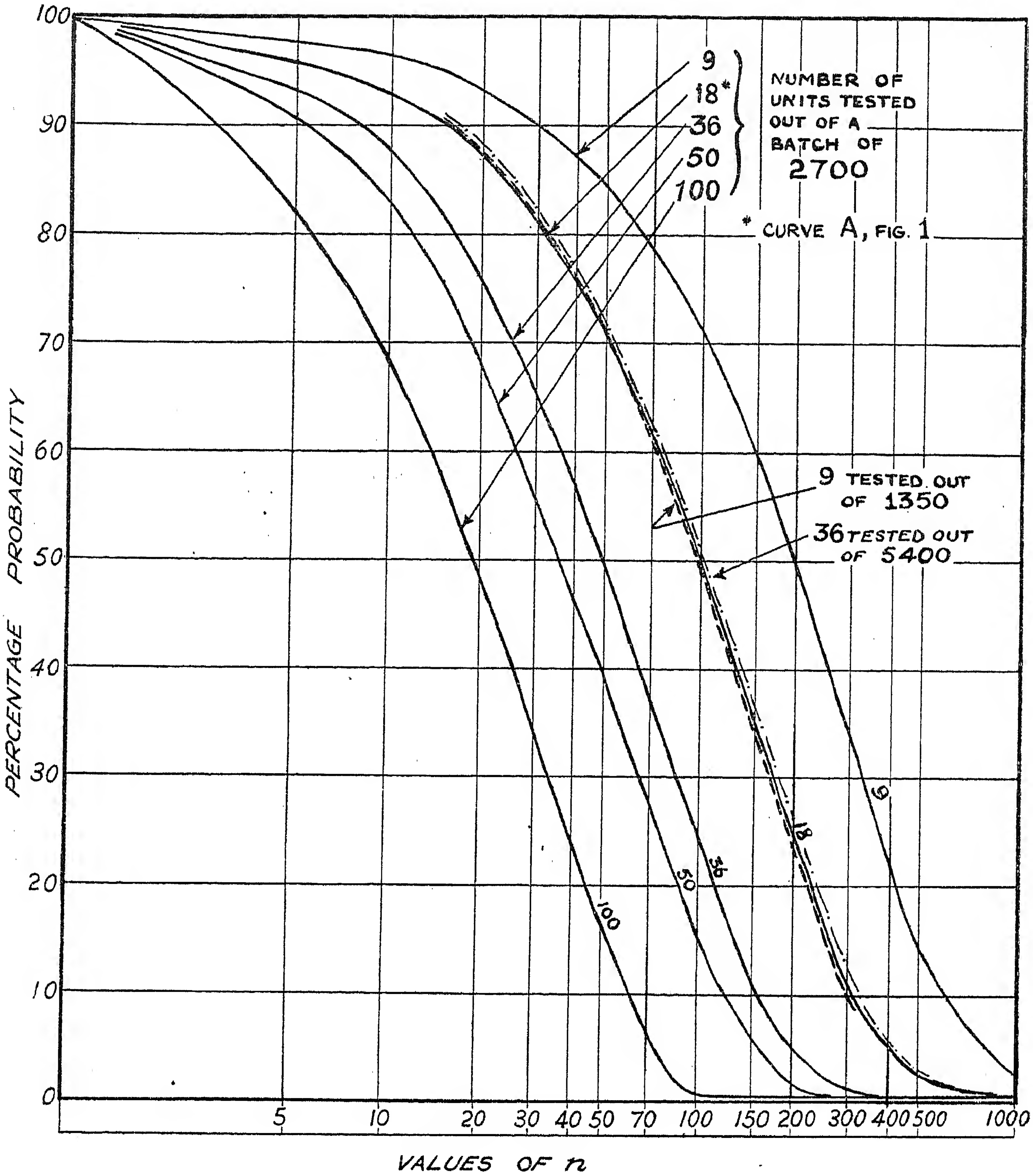

Fig. 7.—Probability of a batch containing n defective units passing on the first test where samples of various sizes are selected for type-testing.

and although curve H leads to the rejection of a rather higher percentage of batches containing only a few defective units it is far superior in the rejection of highly defective batches.

If we consider the case of a manufacturer who is confident enough in his product to expect only, say, 5 defective units per batch, we find for the two curves that he should have to test the following percentages of units, on an average, in successful batches:

	Curves A and B	Curves H and G
First Test	0·75 in 96%	1·85 in 91%
Second Test	2·25 in 3%	3·7 in 6%
Average percentage of tested units per successful batch	0·79	1·9
Percentage of batches rejected	0·5	3

One might therefore expect the costs of a manufacturer who was sure to that extent to be increased by about 4 % if the specification called for tests on 50 plus 50 units instead of 18 plus 36, and if the rejected batches are regarded as worthless (see Appendix 2).

It is quite possible for the engineers to work out similar curves for any particular scheme they may have in mind, and although the author favours statistical specification levels (which can only be determined after much research but which, once decided upon, are more directly applicable on a general basis) as a future criterion, he is of the opinion that the immediate application of the principles here described would enable engineers to be much surer that their specifications were being substantially fulfilled, *provided that it is legitimate to ignore the possibility of prior tests by the manufacturer.*

It will be appreciated that curves C and H refer only to testing batches of 2 700 units, and that curve D refers to cases where these are to be assembled into strings of 9 in series.

Table 1

Number of defective units per batch of 2 700	5		10		25		50
Tested to curve	H	C	H	C	H	C	H
Rejects at 85 %	3	0·5	7·5	0·8	26	5·8	49·7
Accepts at 100 %	97	99·5	92·5	99·2	64	94·2	50·3
Addition to costs of accepted units to make up loss on rejects	0·5	0·07	1·22	0·12	6·1	0·9	15·0
Percentage destroyed in testing	1·9	0·79	2·02	0·84	2·08	0·91	2·1
Percentage added to costs due to rejections and loss by testing	2·4	0·86	3·2	0·9	8·2	1·8	17·1
Extra cost due to testing to Curve H instead of Curve C, %	1·5		2·3		6·4		13·
Probable percentage of defective strings in service	1·3		3·3		8·0		15·

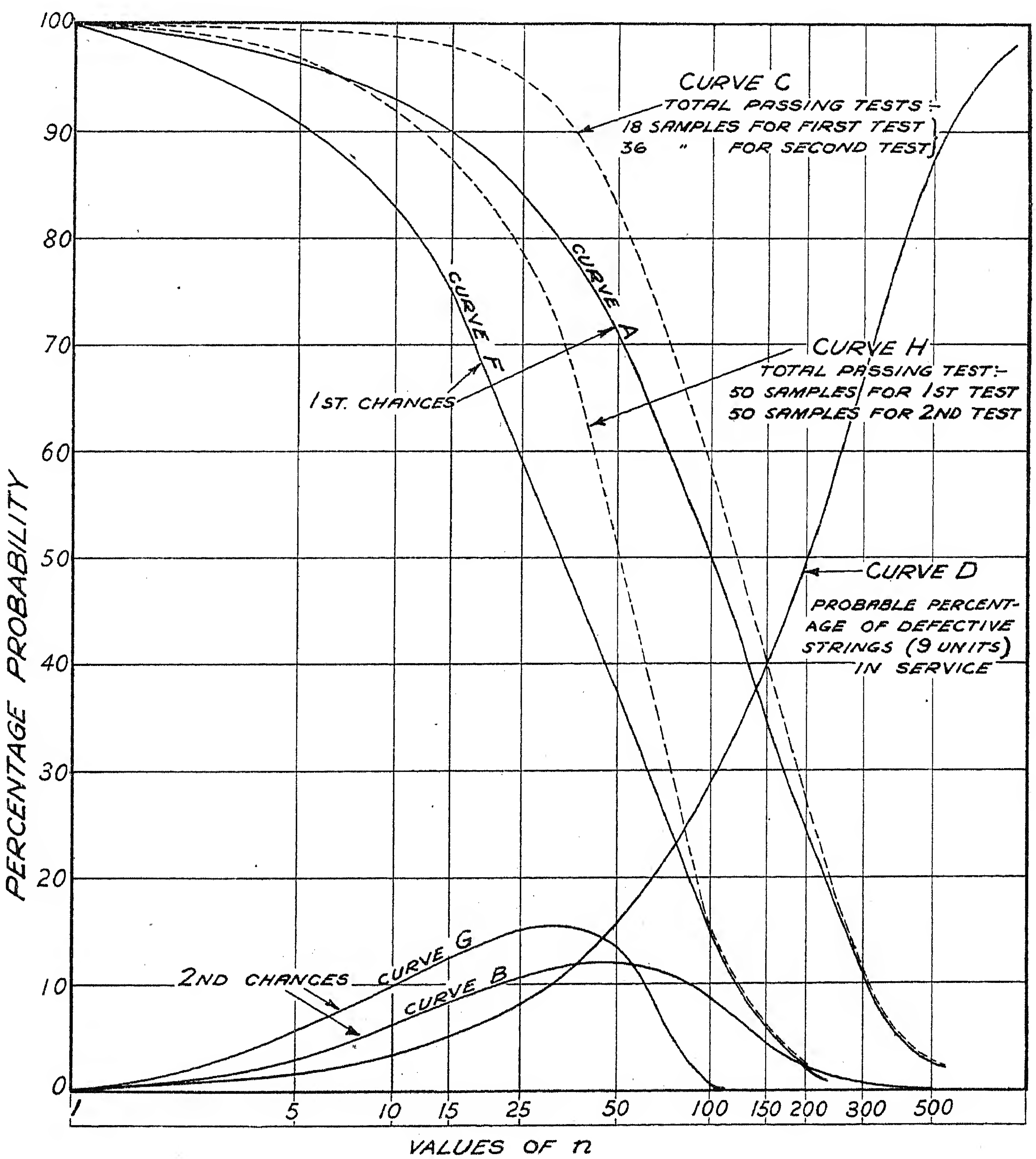

Fig. 8

APPENDIX 2

Table 1 gives some idea of how calling for tests on 50 plus 50 insulator units, instead of on 18 plus 36, out of batches of 2 700, would affect manufacturing costs. Although a batch may be rejected for a major specification it is not necessarily a dead loss. It will be sold, as opportunities occur, for use on minor schemes where mechanical strength is not so important. Supposing that the value of a batch is reduced by 15 % on rejection owing to storage charges pending marketing opportunities, which themselves may be less favourable, then Table 1 shows, in the penultimate line, the extra cost of manufacture represented by more rigorous testing under the terms shown by curve H, Fig. 8.

This Table is only an approximation, as many factors may vary. It would, for instance, be more difficult to sell 49·7 % of one's rejects at only 15 % loss than it would be to sell only 3 %. The Table does demonstrate, however, that the price of ensuring a very high probability of passing only slightly defective batches is within the bounds of reason if prior tests may be ignored.

At the same price the standard error in the standard deviation would be reduced from $0\cdot167\sigma$ to $0\cdot1\sigma$.

Manufacturers, incidentally, would be forced to produce batches containing very few defective units, as it would obviously be difficult for them to stand, or pass on, an increased cost such as the extra 13 % which an average of 50 defective units per batch might entail. The extra cost on a batch containing no defective units is 1·1 %.

APPENDIX 3
Effect of Using Double Strings in Tensioning Positions

Curve D, Fig. 1, show the percentage of strings containing 1 or more defective units plotted against the number of defective units in the batch. This curve is re-plotted as curve D in Fig. 9. In certain cases these strings may be mounted two in parallel for tensioning positions. In that case, if x % of the single strings contain one or more defective units, then in

$$100\left[1 - \frac{(100 - x)(100 - x - 1)}{100 \,.\, 99}\right]\% = \frac{199x - x^2}{99}\%$$

of the double strings one or both strings will contain one or more defective units. This percentage is shown in curve Y, Fig. 9. The number of double strings in which *both* strings contain one or more defective units is

$$\frac{x(x - 1)}{99}\%$$

This percentage is shown in curve Z, Fig. 9. Curve Y gives little cause for satisfaction, but curve Z shows that

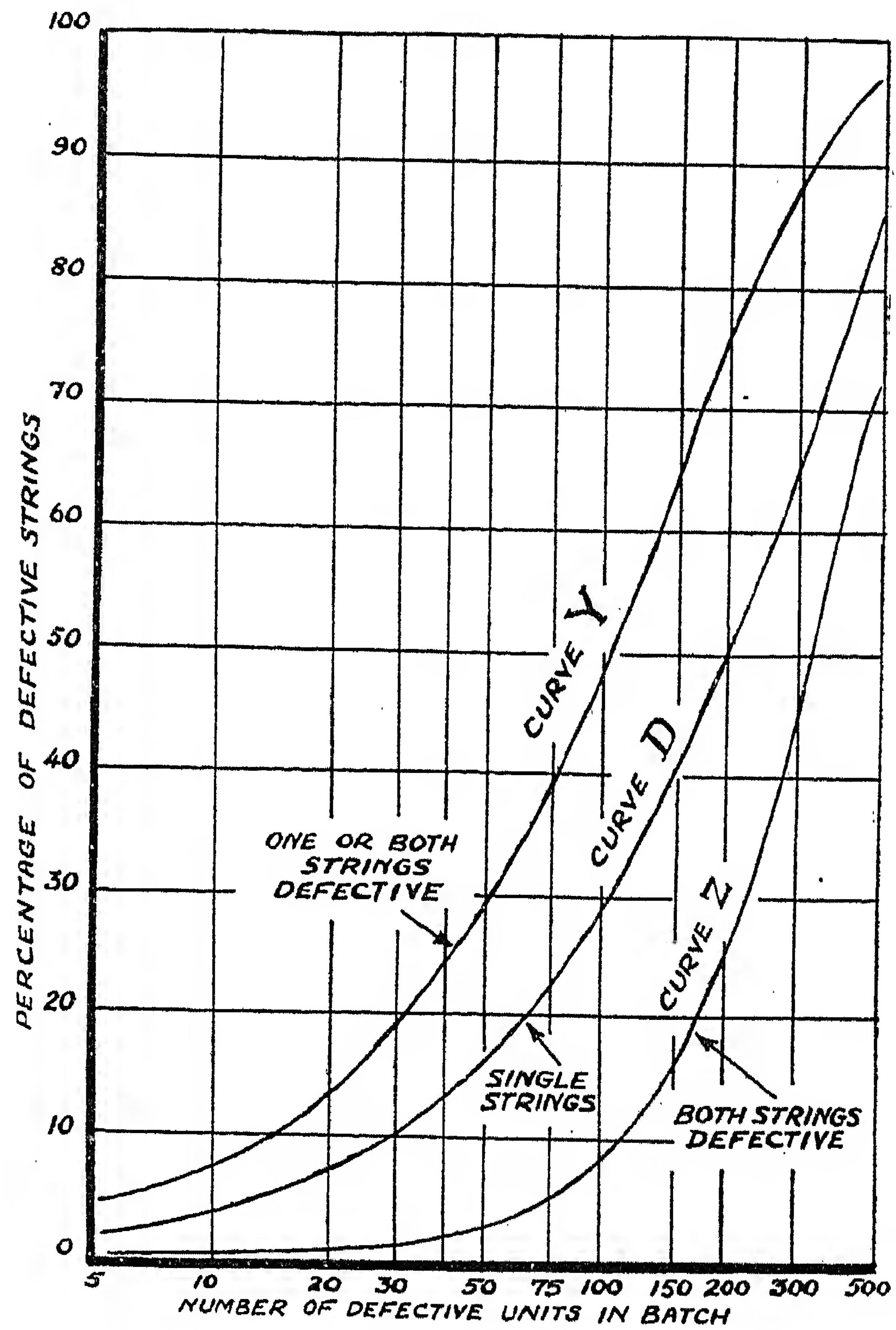

Fig. 9.—Effect of combining 2 strings in parallel at tensioning positions.

very disturbing conditions may arise if we pass an appreciable number of defective units in a batch accepted for service.

It will be noted that the sum of the above terms is, of course, $2x$.

ELECTRICAL INTERFERENCE WITH RADIO RECEPTION

By A. J. GILL, B.Sc.(Eng.), Member, and S. WHITEHEAD, M.A., Ph.D., Associate Member.

(*Paper first received* 21*st October*, 1937, *and in final form* 29*th July*, 1938; *read before the* WIRELESS SECTION, 6*th April*, 1938.)

SUMMARY

The paper describes the method of assessment of the interference to radio reception from electrical equipment, and determines the level to which such interference must be reduced to permit satisfactory service.

The methods of achieving this result are described for the various classes of interfering equipment. Although mainly directed towards the protection of broadcast reception, the principles described apply equally to other radio communication services.

(1) GENERAL

(a) Nature of Interference: Signal/Noise Ratio

Any change in the electrical conditions of a circuit gives rise to a spectrum of components of current or voltage, and the more abrupt the change the higher will be the frequency to which these components extend.* Nearly all classes of electrical equipment are subject to these rapid changes, while, in addition, the apparently continuous wave-shapes of current and voltage possess series of harmonics which may extend into the radio-frequency region. Thus nearly every item of electrical equipment and apparatus may, from the present aspect, be regarded as a potential source of radio-frequency energy. This energy may be transmitted to the aerial of a radio receiver, producing a radio-frequency interfering voltage v at its input terminals with corresponding unpleasant sounds in the loud-speaker, or other reproducing apparatus.

The interfering voltage v is received simultaneously with a modulated carrier which, if conditions are to be tolerable, must be much greater than v, the effect of the latter being the more pronounced in the passages of lighter modulation. Thus the conditions of reception to be assumed in evaluating v are those corresponding roughly to the presence of a large unmodulated carrier. A suitable output voltmeter must be such that, if connected in parallel with the receiver output in the conditions defined, it gives equal indications when interfering voltages of different types, applied to the receiver, produce noises in the loud-speaker judged by listeners as of equal disturbing effect on a programme which may be superimposed on the noise. Such a meter, as regards pure continuous notes, would follow more or less the response/frequency characteristic of the ear. A frequency-weighting curve of this type is shown in Fig. 1.† This subject has received extensive study by the International Advisory Committee for Long-distance Telephone Communication in connection with line communication, but in telephone practice the properties of the receiver mainly determine the phenomena. In radio communication the noises are usually either discontinuous or of such complex character that the charging and discharging times are of more consequence than the frequency response.* As a result of the work of the Comité International Spécial des Perturbations Radiophoniques† (C.I.S.P.R.) a voltmeter fulfilling the above conditions has been specified as a peak voltmeter of linear scale over the working range having a charging time of 1 millisec., a discharging time of 160 millisec., and an indicating-needle time-constant of 160 millisec. The instrument is critically damped. A frequency filter added to give a

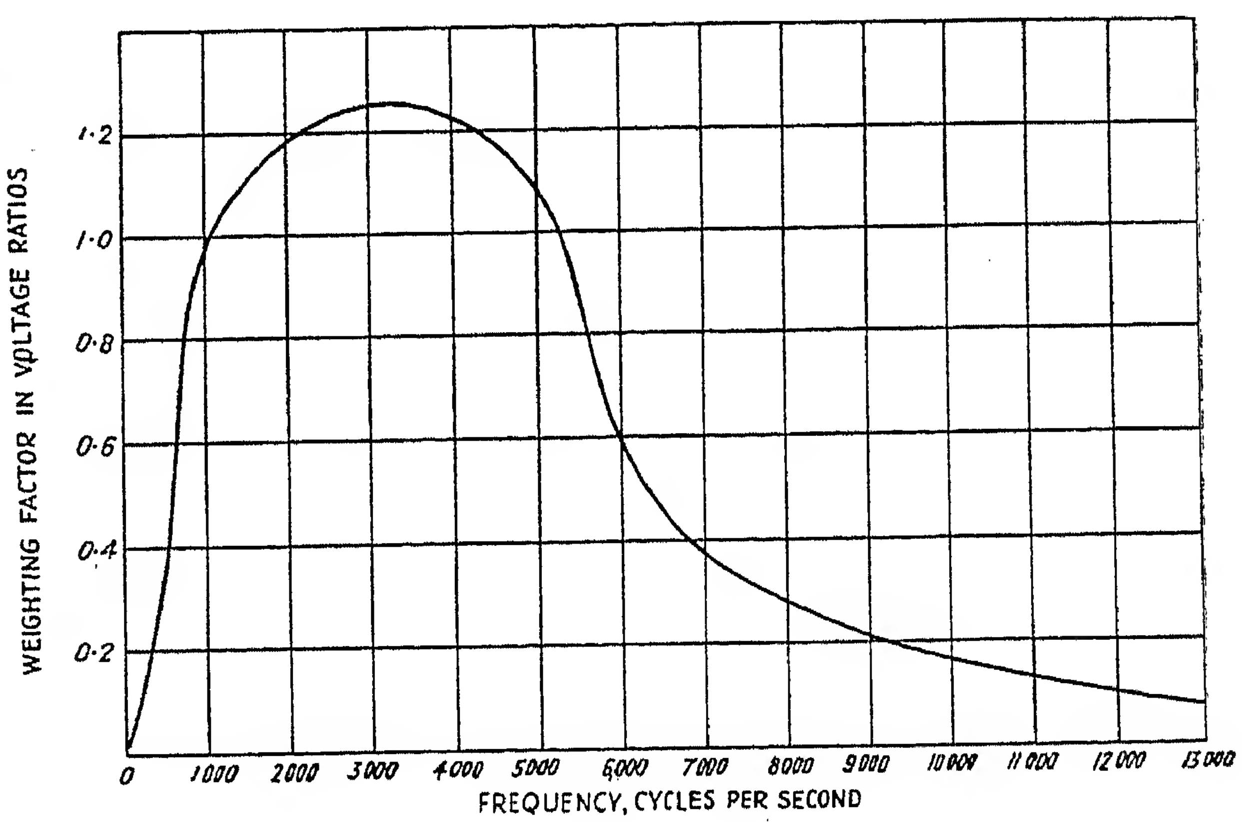

Fig. 1.—Weighting curve for broadcast psophometer (C.C.I.F., Budapest, 1934).

response similar to that in Fig. 1 has been shown to add little to the accuracy.

This specification does not deal with the effect of duration and frequency of repetition of the interference, features which are often very difficult to define for a given type of disturbance. Accordingly it is usually satisfactory to take the largest values observed which occur at all frequently. The standard adopted by the B.S.I. is to take any steady reading if it is maintained beyond 10 sec. or exceeds on the average a duration of 1 sec. per hour, or any interference, however short, if repeated oftener than once in 10 minutes. A large tolerance must in any case be allowed in respect of accuracy of measurement. Regularly-repeated interference will give indications corresponding to a single impulse if the interval between successive impulses is greater than about 0·2 sec.

* For example, a square-topped pulse of time-of-passage t gives rise to a spectrum of an intensity, in the band comprised between the wavelengths λ and $(\lambda + d\lambda)$, which is jointly proportional to $\sin^2(2\pi ct/\lambda)$ and to the band width $d\lambda$, where c is the velocity of light. Any given pulse can be derived by summation of such elements.

† See Proceedings of C.C.I.F., 1934, vol. 4, p. 258 (Budapest Meeting).

* K. MULLER and U. STEUDEL: *Veröffentlichungen aus dem Gebiet der Nachrichtentechnik*, No. 2, 1935.

† See Reports (RI)3 and (RI)4 of the I.E.C.; also B.S.S. No. 727—1937.

On the other hand, if the interval is less than about 0·1 sec. the voltmeter will give a reading approaching closer to the peak value of the interference. If the individual impulses are of a rapidly transient character the increase in indication of the voltmeter, as the impulses are repeated with a greater frequency, may be much greater than the corresponding increase of subjective impression. This source of error is rarely important with interference on the normal broadcast wavelengths, but with ignition systems the range of spark frequency may include the frequencies corresponding to the discharge time-constant of the voltmeter. The difficulty is conveniently overcome by referring the interference to a "normal" spark frequency.

The greater the proportion of soft or lightly-modulated passages in a programme the greater will be the disturbing effect on it of a given interference. Speech and music differ also in intrinsic liability to disturbance. A number of tests were made by the C.I.S.P.R. in which various observers adjusted the level of different types of interference, superposed on a range of representative programmes, until it was judged just tolerable. The interference was measured by the voltmeter already specified, and the programmes by a peak-voltage indicator. The signal(programme)-to-noise ratio so determined as corresponding to the limit of toleration was then found to be substantially independent of the observer, type of programme, and type of noise, provided that the maximum level, i.e. the peak of the dynamic characteristic* of the programme, was taken. In these circumstances the limiting signal/noise ratio was found to be 40 db., the same ratio as that applying to interference between neighbouring transmissions. Now the peak of the dynamic characteristic corresponds to the peak modulation of the transmission In general broadcasting practice the peak modulation level is usually taken as 80 %, so that the general criterion of "freedom from interference" is that the noise due to the interference, measured by the voltmeter specified, should be at least 40 db. below the level arising from the transmission to be protected when having a degree of modulation of 80 %. The same principles will apply to the sound transmission accompanying television. The requirements for the vision transmission have not yet been decided. Experience (mentioned later) so far suggests that the sound is more sensitive to interference than the vision; so that, from the point of view of interference, television may be conservatively regarded for the present as an ultra-short-wave broadcast.

(b) Measurement of Interference

Let it be assumed that an ideal receiver selects a band of frequencies, rectifies the resultant in the manner known as linear, and rejects all except a certain band of low frequencies, but otherwise has no action upon the input signal apart from a constant amplification of the frequencies selected. Then it may be shown (as in the Appendix) that if the incoming signal is

$$P(1 + M\cos pt)\cos \omega t + \Sigma v_n \sin(\omega_n t + \phi_n) \quad . \quad (1)$$

then the low-frequency output is, in certain conditions,

$$V = \text{Const.} \times \left\{MP\cos pt + \Sigma v_n \sin\left[(\omega_n - \omega)t + \phi_n\right]\right\} \quad (2)$$

We may regard P as the intensity of the carrier, and $M\cos pt$ as its degree and type of modulation, while $v_n \sin(\omega_n t + \phi_n)$ is a radio-frequency interfering voltage lying in the band accepted by the receiver.* Thus

$$\text{Signal/noise ratio} = MP/\Sigma v_n \quad . \quad . \quad . \quad (3)$$

both quantities being measured by a meter of suitable response. From the preceding section, M must be taken as 0·8 (i.e. 80 % modulation) in determining whether the

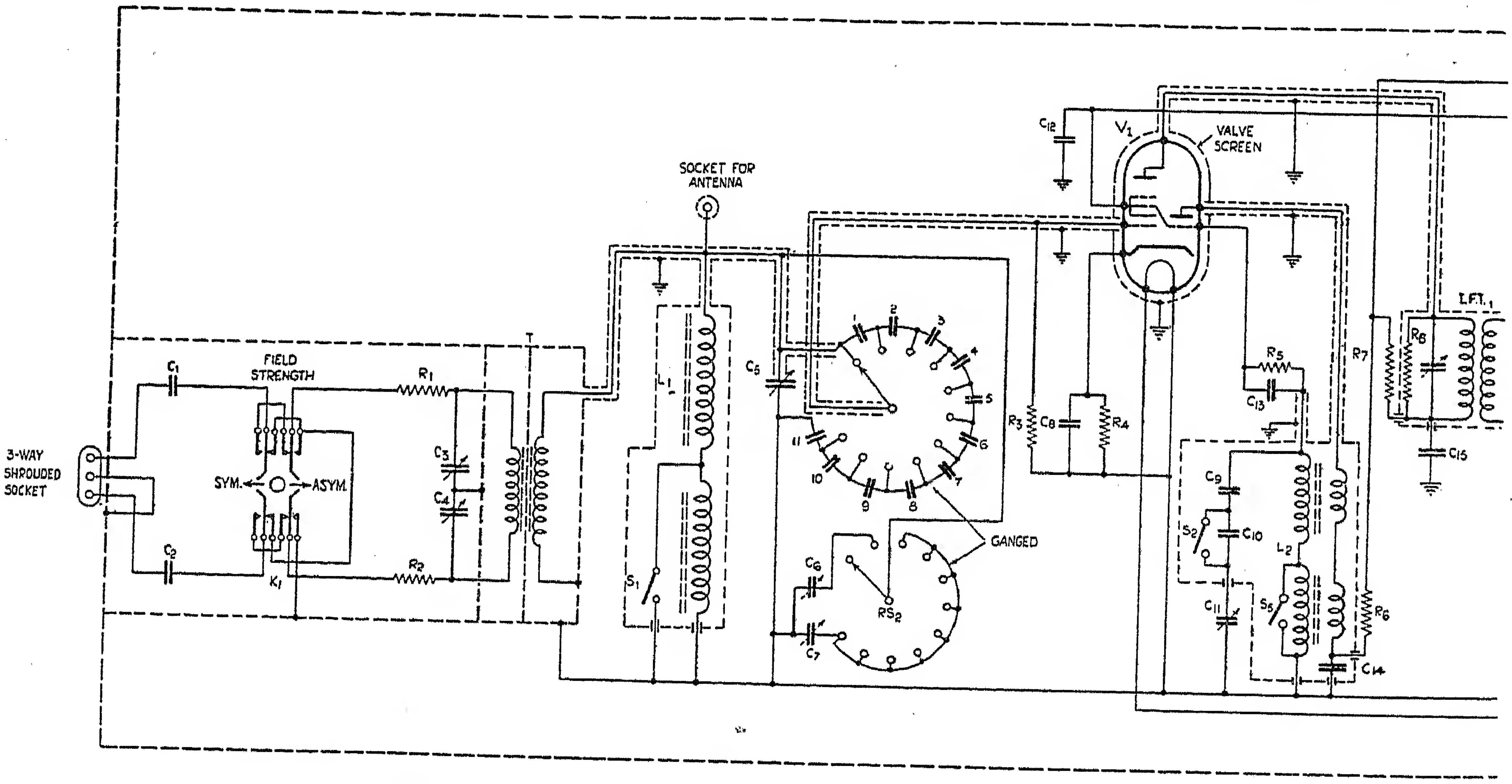

Fig. 2.—G.P.O. portable radio-interference measuring set.

* Subject to the maximum level being attained or exceeded for reasonable periods, e.g. at least about 5 % of the programme time.

* Assuming that the h.f. band-width corresponds to, or is narrower than the l.f. band-width.

interference is tolerable. Thus the signal/noise ratio is numerically equivalent to $0 \cdot 8$ times the ratio of the carrier amplitude to the integral of the high-frequency interference spectrum over the band width selected, provided this integration is made in such a way as to take account of the time-constants of the voltmeter specified. This leads to the important conclusion that the relative interfering effect can be expressed as a property of its high-frequency spectrum (selected and integrated in a defined manner) independently of the signal which is disturbed. This interfering quality should be measurable, in the absence of a signal, by a suitable high-frequency (h.f.) voltmeter. If the noise voltmeter previously defined had been a simple peak voltmeter a similar h.f. peak voltmeter would have been an equivalent noise-indicator. Nevertheless, it is shown in the Appendix that an h.f. voltmeter of the same time-constants should give indications approximately equivalent to those given by the noise voltmeter defined.

The validity of the foregoing analysis requires the following conditions in the ideal receiver to which it refers:—

(i) The receiver is of perfect linearity and fidelity.

(ii) The band width is selected by the h.f. stages, the low-frequency (l.f.) stages imposing only an equivalent limitation such that terms of frequency greater than the maximum modulation frequency permitted by the band width are eliminated.

(iii) The signal carrier is very large compared with the interference.

(iv) The reaction of the sidebands of the signal on the interference is neglected.

It is shown in the Appendix that in the absence of the signal the low-frequency output of the receiver is given approximately by:—

$$V = \text{Const.} \times \Sigma v_n \sin \left[(\omega_n - \omega')t + \phi_n\right] \quad . \quad (4)$$

where ω' is the frequency of rectification, both ω' and ϕ_n being actually variable. Although (4) obviously differs considerably from the second terms of (2) if n is small, it is shown in the Appendix that when n is large (i.e. when the interference spectrum tends to be continuous, as is usual in practice) the maximum value of (4) is probably equal to the maximum value of the interference terms in (2), so that the carrier may often be omitted in measuring the interference, without great error.

The average listener's receiver falls short of the ideal, but two possible defects are easy to assess. The standard band-width adopted is that corresponding to the transmission of frequency-displacements from 100 to 4 500 cycles per sec. within the following tolerances: $+ 1 \cdot 5$ db. and $- 20$ db. with respect to the response of the carrier frequency for frequencies displaced less than 100 cycles per sec.; $+ 1 \cdot 5$ db. and $- 6$ db. from 100 to 200 cycles; $+ 1 \cdot 5$ db. and $- 1 \cdot 5$ db. from 200 to 2 000 cycles; $+ 1 \cdot 5$ db. and $- 6$ db. from 2 000 to 4 000 cycles; $+ 1 \cdot 5$ db. and $- 20$ db. from 4 000 to 5 000 cycles; $- 6$ db. and $- 20$ db. from 5 000 to 10 000 cycles; response less than $- 20$ db. for frequencies displaced more than 10 000 cycles. When completed, the ideal characteristic will presumably be that of the standard apparatus of the C.I.S.P.R. now in construction. If the actual band-width differs from this, then the interference, if of the continuous-spectrum type, will vary proportionately with the integral taken over the selectivity (response/frequency) curve, while the broadcast signal will usually be affected to a smaller extent.* With a narrow band-width the effects tend to be the same for both, and the signal/noise ratio is not affected. If the rectification is non-linear the signal/noise ratio is still approximately given by (3). Mumford† has shown that,

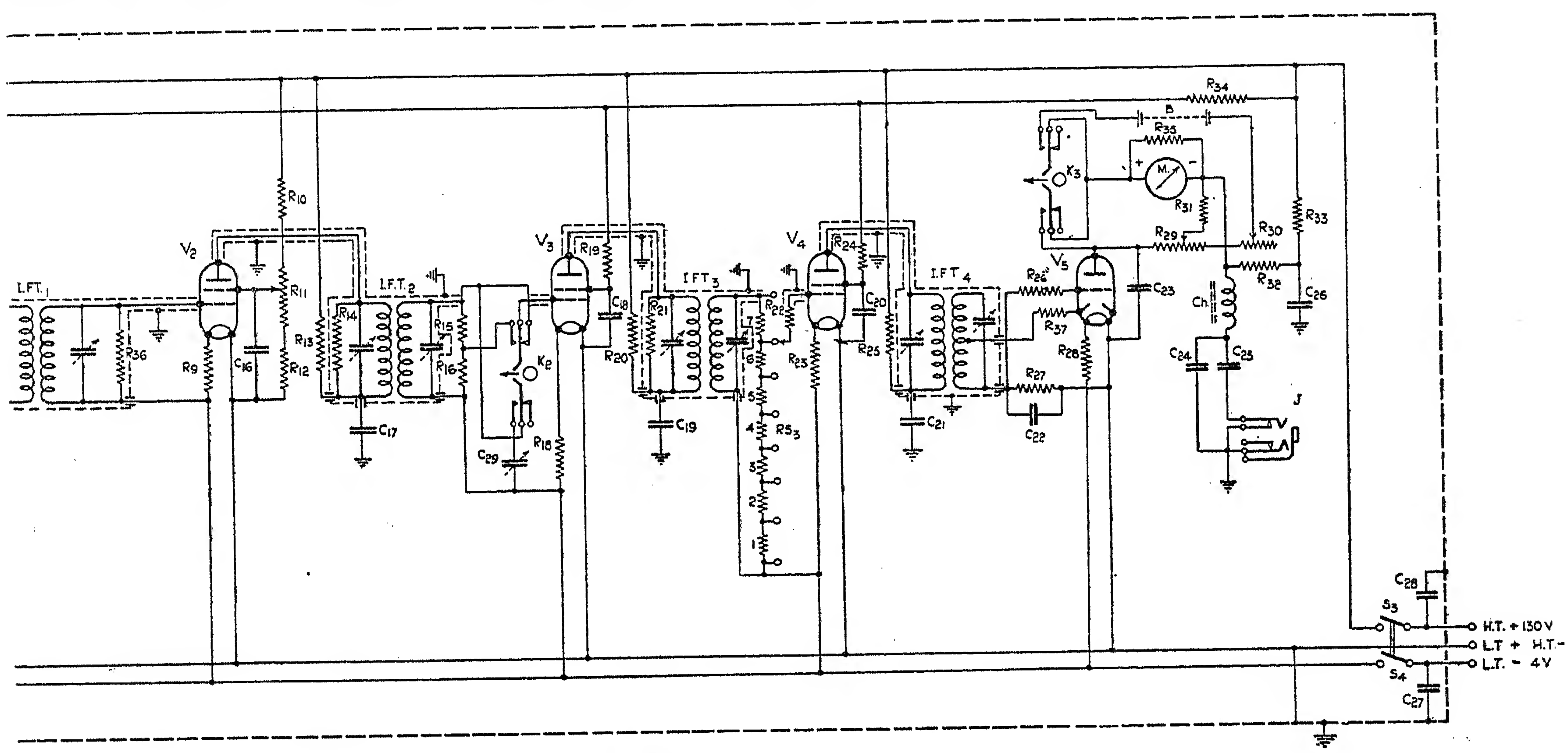

Fig. 2 (continued).

* A narrow band-width diminishes the broadcast sidebands, while a wide band-width introduces demodulation effects.

† A. H. Mumford and J. L. Howard: Radio Report No. 277, 1934 (P. O. Engineering Department). See also A. H. Mumford and H. Stanesby: Radio Report No. 300, 1934 (P.O.E.D.); and J. W. Alexander: *Hochfrequenztechnik und Elektroakustik*, 1932, vol. 40, p. 82.

neglecting the signal sidebands and intermodulation products of the interference, this conclusion is strictly true as regards r.m.s. values in square-law rectification, and his analysis will lead also to the more general indication that the conclusion is roughly true as regards the modified peak values, provided the rectification follows a power law with index between 1 and 2.

It is possible by the means described to make an absolute measurement of the interfering quality of the voltage appearing at the listener's aerial, but to characterize the disturbing effect of a source of interference it is necessary to consider the coupling between the source and the listener. When the interference is directly radiated, its field strength may be found, using a calibrated aerial in conjunction with a measuring set of the defined characteristics, and may be specified at the minimum distance at which a listener's aerial may reasonably be situated; or the field-strength distribution may be plotted and directly compared with the assumed or measured broadcast field-strength. As regards indoor aerials, the broadcast field and, where possible, the interfering field, in free space in the immediate neighbourhood of the listener are considered. Often, however, the interference is partly conducted, as by the electric mains, and then radiated therefrom to the listener's aerial. It is then sometimes possible to determine a statistical average field-strength of the radiating system when excited by the various sources normally operating.* The more important instance of the domestic electric mains† does not permit the satisfactory definition of a field strength and accordingly the ratio A of the interfering voltage at the listener's aerial to the interfering voltage at the terminals of the disturbing item is measured and known as the "coupling factor." The effective height h of the listener's aerial referred to the broadcast field in the neighbouring free space is also measured. Then if V is the interfering voltage of the item and ϵ the broadcast field the condition for good reception is that—

$$V \leq 0\cdot 008\frac{h\epsilon}{A} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

A statistical analysis of the quantity (h/A) permits the determination of the limiting value of V, and the interfering quality of the item can be characterized by the measured value of V. It is necessary to consider both the voltage which may exist between the terminals of the item and the voltages between the terminals, which may be connected together for this measurement, and earth.‡ The former voltage is known as the "symmetrical voltage" and the latter as the "asymmetrical voltage." In addition, the disturbing voltage is profoundly influenced by the external h.f. impedance applied to the item through the system connected thereto. The conditions, in these respects, under which the item is tested must therefore be carefully defined for each type of disturbing source.

(c) Comparison of Various Methods

The foregoing principles lead to three types of measuring equipment. In the first method an artificial carrier may be injected at the input or at the detector, and the special voltmeter defined measures the l.f. output. This method is employed in the Siemens and Halske apparatus,* which comprises a 2-stage h.f. amplifier tuned to the injected artificial carrier, a square-law detector, which functions linearly owing to the large carrier, and an l.f. amplifier and special voltmeter. A simplified version employs an oscillating detector and a voltmeter consisting of a single valve. A feature of the standard apparatus which seems open to question is that the band width is partly selected in the l.f. stages after detection.

In the second method the special voltmeter is used in conjunction with a suitably selective h.f. amplifier as a high-frequency valve-voltmeter. This method has been adopted by the G.P.O. and the E.R.A., although a number of tests have been made by the previous method. Besides the use of standard field-strength-measuring equipment, the G.P.O. have designed a portable testing set, shown in Fig. 2 and described in B.S.S. No. 727—1937. It comprises a superheterodyne amplifier and incorporates means for calibration, *in situ*, by observing the indication due to the thermal agitation in the first tuned circuit. A similar set having a range from 12 to 2 000 m. has recently been constructed. The E.R.A. set for the broadcast ranges (Fig. 3) employs a buffer-amplifier type of tuned amplifier. Means are incorporated for checking battery voltages and currents, and the apparatus has been found sufficiently constant in use to need only an occasional recalibration by a standard signal. Both the G.P.O. set and the E.R.A. set employ a vertical-rod aerial in measuring the field strengths and are adapted for measuring interfering voltages by means of a balanced and screened input transformer. The E.R.A. short-wave measuring set (Fig. 4) is only adapted for measuring field-strengths using a frame or vertical-dipole aerial. It is similar to the G.P.O. apparatus in employing the superheterodyne principle (the intermediate frequency is 1 Mc.) but is directly calibrated for field strength by the radiation from a given loop carrying a known current at a standard distance. Recently the h.f. method has been adopted in the standard C.I.S.P.R. apparatus now in construction, and has also been used in the U.S.A.†

The third method, the measurement of the l.f. output of the interference in absence of a carrier, is employed in less accurate, in comparative, and in qualitative, tests, and can be applied to a calibrated radio receiver equipped with a suitable output voltmeter. The N.E.L.A.‡ in America standardized this method, specifying the selectivity and fidelity curves. The h.f. band-width so defined is rather less than 9 kc., but the l.f. fidelity corresponds roughly to the C.I.S.P.R. definition. No acoustic frequency-weighting is employed, and the integration time, determined by the meter needle, is of the order of 0·3 sec. A transfer standard method is adopted, a multivibrator (120 cycles per sec. fundamental frequency) being adjusted to give the same reading as the interference. The output of the multivibrator is cali-

* The method followed with traction and communication systems, etc.
† F. Eppen and K. Müller: *Elektrische Nachrichten-technik*, 1934, vol. 2, p. 257.
‡ K. Müller: *Veröffentlichungen aus dem Gebiet Machr. Techn.*, 1934, vol. 4, p. 139; W. Wild: *Elektrotechnische Zeitschrift*, 1933, vol. 54, pp. 149, 172.

* Siemens and Halske Publication No. 491 C.; W. Wild: *loc. cit.*; J. Schmied: *Elektrotechnik und Maschinenbau*, 1935, vol. 53, p. 373.
† F. O. McMillan and H. G. Barnett: *Transactions of the American I.E.E.*, 1935, vol. 54, p. 857.
‡ National Electric Light Association Reports Nos. 32 and 33; *General Electric Review*, 1933, vol. 36, p. 201.

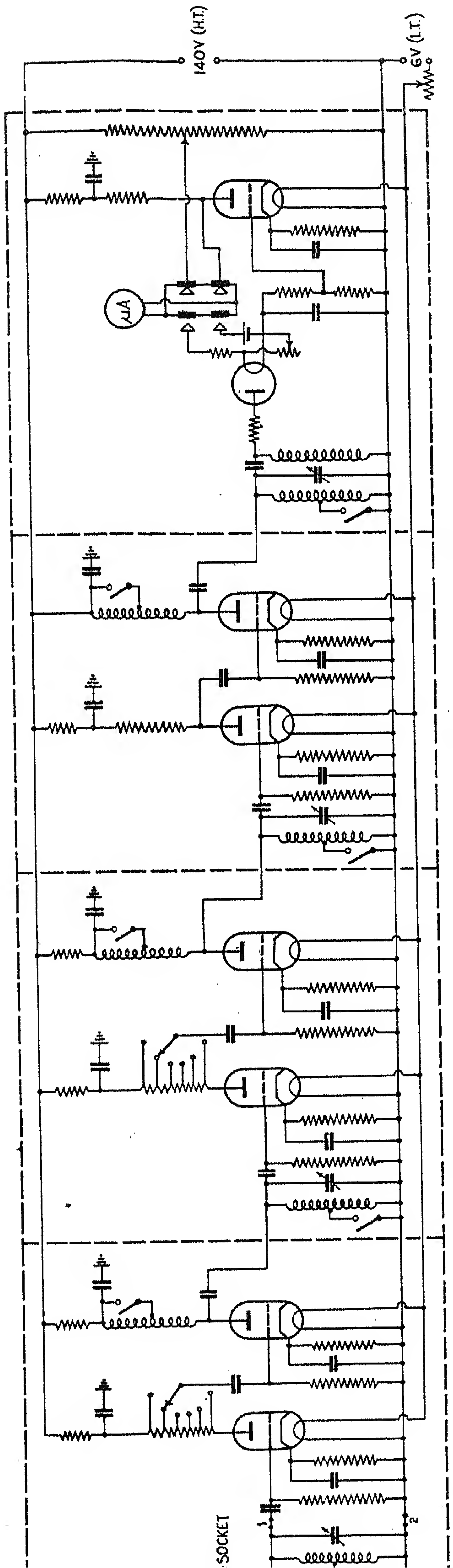

Fig. 3.—E.R.A. broadcast-frequency interference-measuring set.

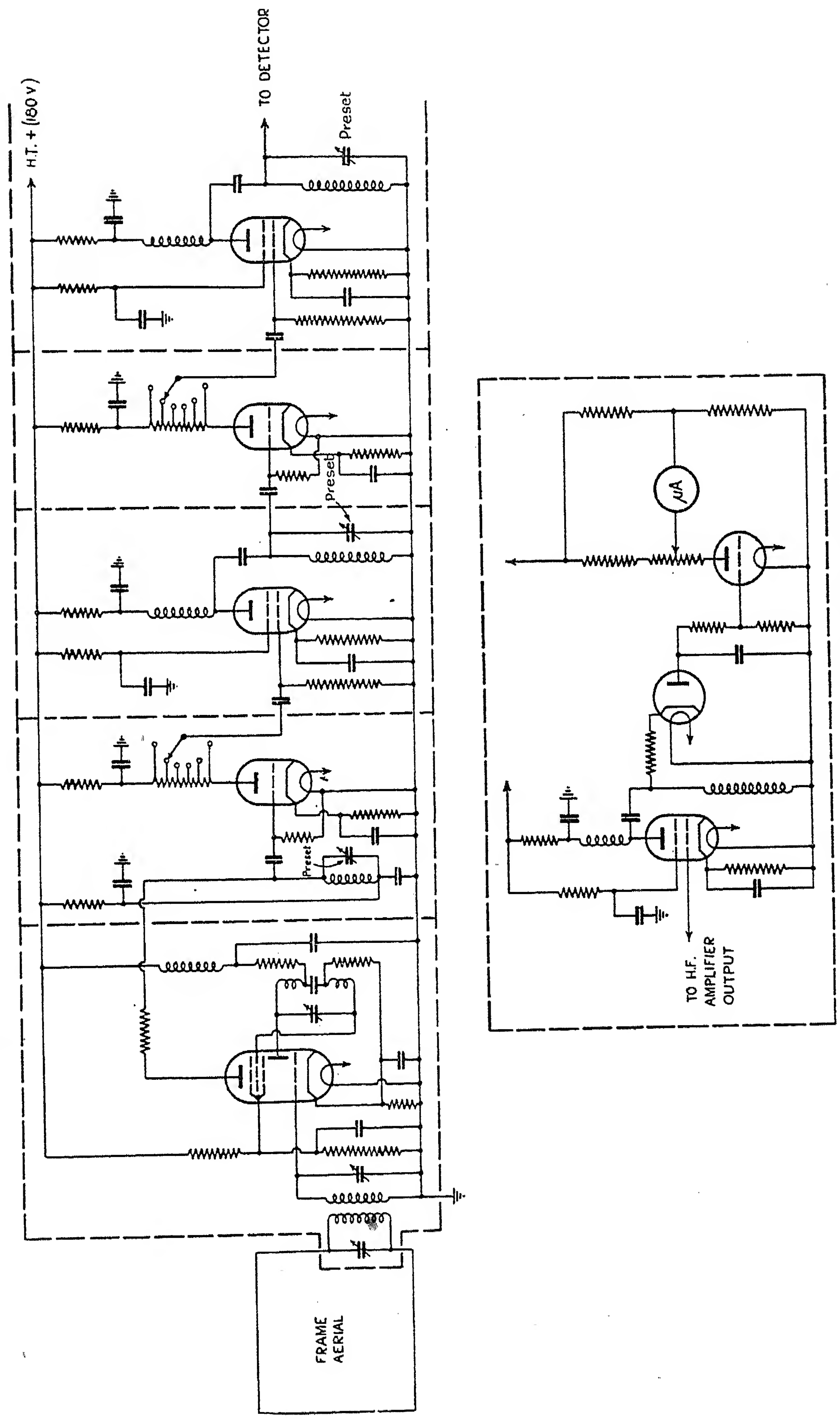

Fig. 4.—E.R.A. short-wave measuring set.

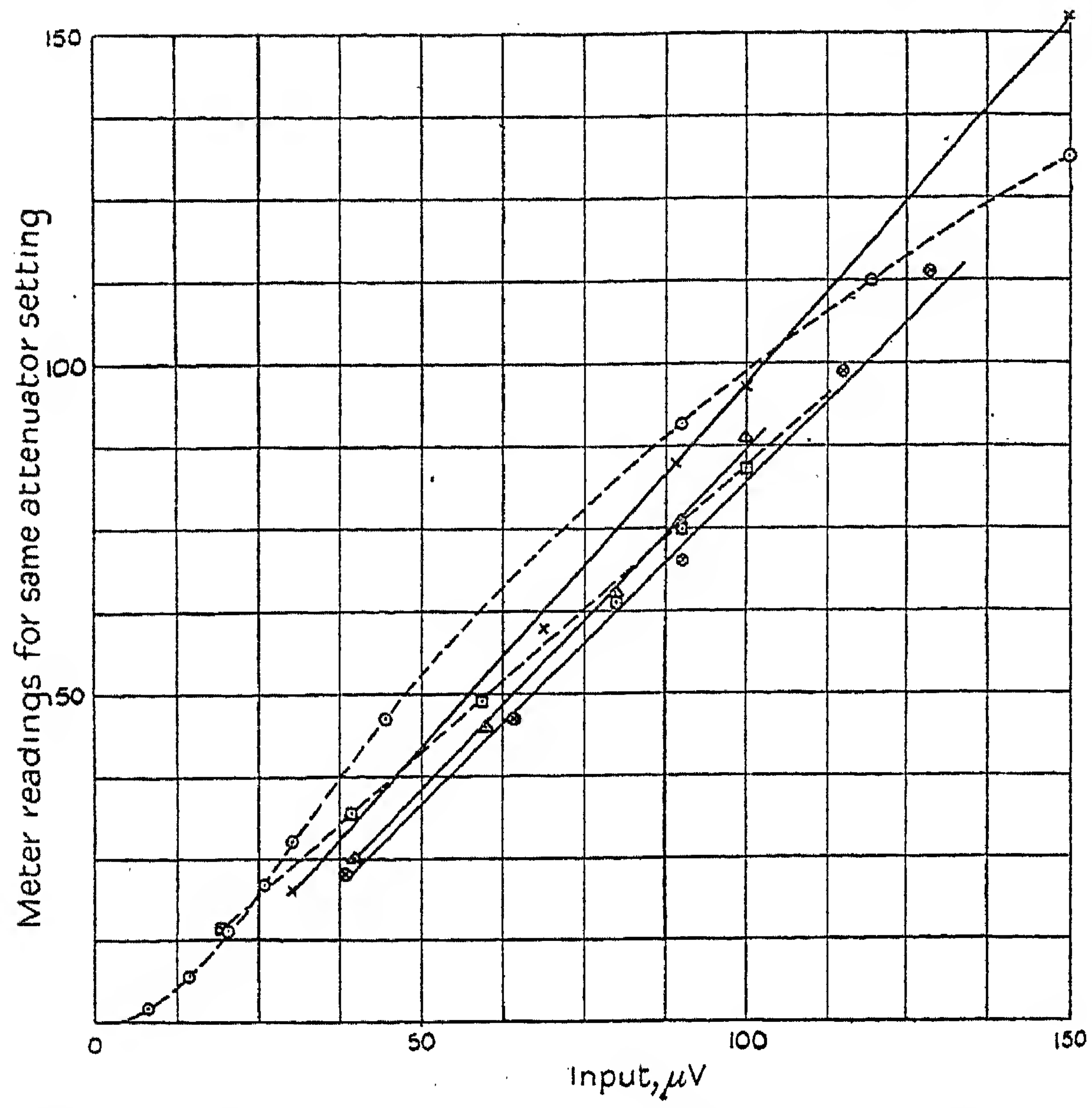

Fig. 5.—Effect of simple signals with different methods of measurement.

	First method	Second method	Third method
Signal	L.F. voltmeter with carrier	H.F. voltmeter	L.F. voltmeter without carrier
Single frequency	- - ⊡ - - 0·4 kc. from carrier	——X——In tune ——△——Displaced 0·4 kc. from peak	No reading
Wave modulated 30 % at 0·4 kc.	Same as third method in this case	——⊗——Corrected for crest value	- - ⊙ - - Corrected for modulation percentage

The E.R.A. receiver was arranged to make measurements according to any of the three methods. Fig. 5 shows that the reactions to standard signals follow the elementary theory. An unmodulated wave gives the same readings with the first two methods and no reading with the third. If a wave modulated to a depth M is applied the first method gives $(1 + M)$ times the carrier (peak h.f. voltage), while the second and third methods are identical and give the modulation M. The readings are corrected by the factors mentioned, and the agreement is within the differences caused by the selectivity, curvature, and lack of perfect linearity in rectification. Similar comparisons between the first and second methods were made by the G.P.O. and E.R.A. with different sources of interference, as shown in Table 1.

Thus the first and second methods, which are theoretically equivalent, are also equivalent in practice, allowing for the difficulty of reproducing accurately the interference tested. The complexity of the interference employed in these tests is evidenced by the fact that an average h.f. voltmeter gave results differing from those referred to in Table 1 to a mean extent of 8 db., and in some cases by 10–20 db. Comparison (49 tests) between the G.P.O. and E.R.A. sets, both following the second method, gave a mean difference of 0·12 db. and a maximum difference of 4 db. A similar comparison was made between the G.P.O. and the Siemens and Halske sets, the latter embodying the first method. The mean difference was 3 db. and the maximum 6 db.

Provided the characteristic of the measuring apparatus is accurately linear and the interference has a continuous and fairly uniform spectrum, the presence of the carrier, wherein the first method differs from the third, has not a very great effect. This was verified both with artificial and with normally-radiated carriers in tests on interference from trolley-buses and also (artificial carrier only) in tests on domestic items. In any case, the ratio of unsuppressed to suppressed levels is less affected by the carrier than absolute values, so that earlier work on such ratios by the third method remains substantially valid.

The importance of polarization in interference measurements is mainly confined to frequencies above 20 Mc., where also regard must be paid to reflection, wave-front

Table 1

Tests made by	Source of interference	Difference* (db.) Max.	Difference* (db.) Mean
E.R.A.	(1) Buzzer of telephone noise unit	+ 2	+ 1
	(2) Fractional-h.p. motor	+ 4	+ 3
	(3) Magneto ignition system	− 5	− 1
	(4) Dynamo and commutator (square impulses)	− 2	− 0·5
	(5) N.E.L.A. multivibrator	+ 4	0
G.P.O.	(6) Vacuum-cleaner motors (fractional-h.p. universal type) ..	+ 2	+ 1·5
	(7) Wheatstone transmitter run at 10 speeds varying between 1 and 90 pulses per sec.	+ 3	+ 1

* A plus sign means that the l.f. voltmeter with carrier gave higher readings than the h.f. voltmeter without carrier.

brated in terms of a standard signal modulated at 400 cycles per sec. to a depth of 40 %. Similar equipment, with the addition of an acoustic filter adjusted to Fig. 1, was used in France,* but the C.I.S.P.R. methods are now followed.

* H. SUBRA: *Annales des Postes, Télégraphes, et Téléphones*, 1935, vol. 24, p. 368.

distortion, etc. A reasonable degree of consistency has been obtained with the E.R.A. receiver by orienting the frame to give the maximum reading and by taking a mean for several points in the neighbourhood of the test position. The signal/noise ratio has been found in tests on various types of interference to be the same for a vertical-dipole as for a frame aerial. Table 2 gives the results of some subjective tests carried out on the B.B.C. television service.

Table 2

Type of interference	Tolerable signal/noise ratio, db.		Remarks
	Sound	Vision	
Valve electrotherapy apparatus (unsmoothed a.c.)	40	16–17	The h.f. band-widths of the receivers employed were 60 kc. for the sound transmission and 4 Mc. for the vision transmission. Ratio of interfering field by frame aerial to value by dipole aerial was $+0\cdot6$ db. at $41\cdot5$ Mc. and $-2\cdot5$ db. at 45 Mc.
Ignition systems	30–43	21–24	
Contactors	34	33	

(2) SOURCES OF INTERFERENCE

(a) Radiated Interference

(i) Trolley-buses.

Although included for convenience in the present Section, the interference arising from the operation of a trolley-bus is mainly radiated from the overhead contact wires along which the disturbances are propagated. The direct radiation from the vehicle itself is rapidly attenuated with distance and is usually less than 10 μV per metre beyond about 20 yards. The radiation from the overhead system extends along the wires for a considerable distance, sometimes along the whole system, and may exceed 10 μV per metre at distances from the track up to $\frac{1}{2}$ or 1 mile. Fig. 6 shows the variation, with distance from the track, of the field strength of the interference caused by a vehicle passing opposite the test point. In the tests shown in Fig. 7 the interference did not vary greatly with frequency, but differences in this respect are encountered in different systems. The sources of interference on a trolley-bus are the collectors, the main contactors supplying and controlling the motors, the relay circuits controlled by the driver which operate the contactors, the driving motor, the brake (exhauster or compressor) motor, and the motor-generator (if present) for lighting. It is desirable also to distinguish between rheostatic braking, where the motors during deceleration are disconnected from the supply and dissipate the brake energy in a rheostat, and regenerative braking, where energy is fed back into the line. Some recent types of trolley-bus combine the two forms, rheostatic braking being employed at low speeds. The interference from trolley-buses is assessed on a field-strength basis and is usually referred either to the maximum recurrent disturbances observed at a distance of 10 yd. from the track, or to observations made underneath the contact wires, at a distance of 40 ft. from the vehicle. Table 3

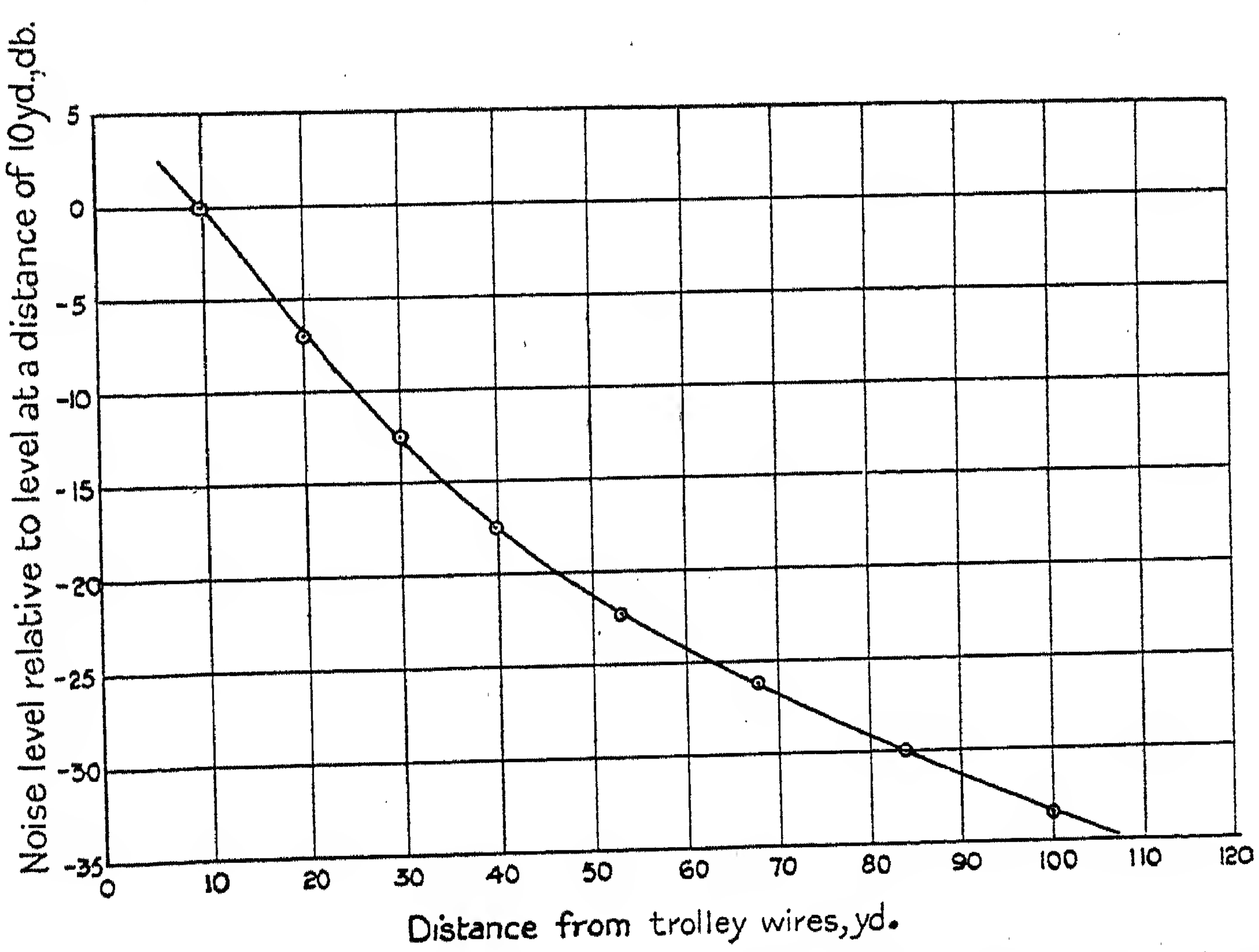

Fig. 6.—Variation of interference due to trolley-buses, with distance from track.

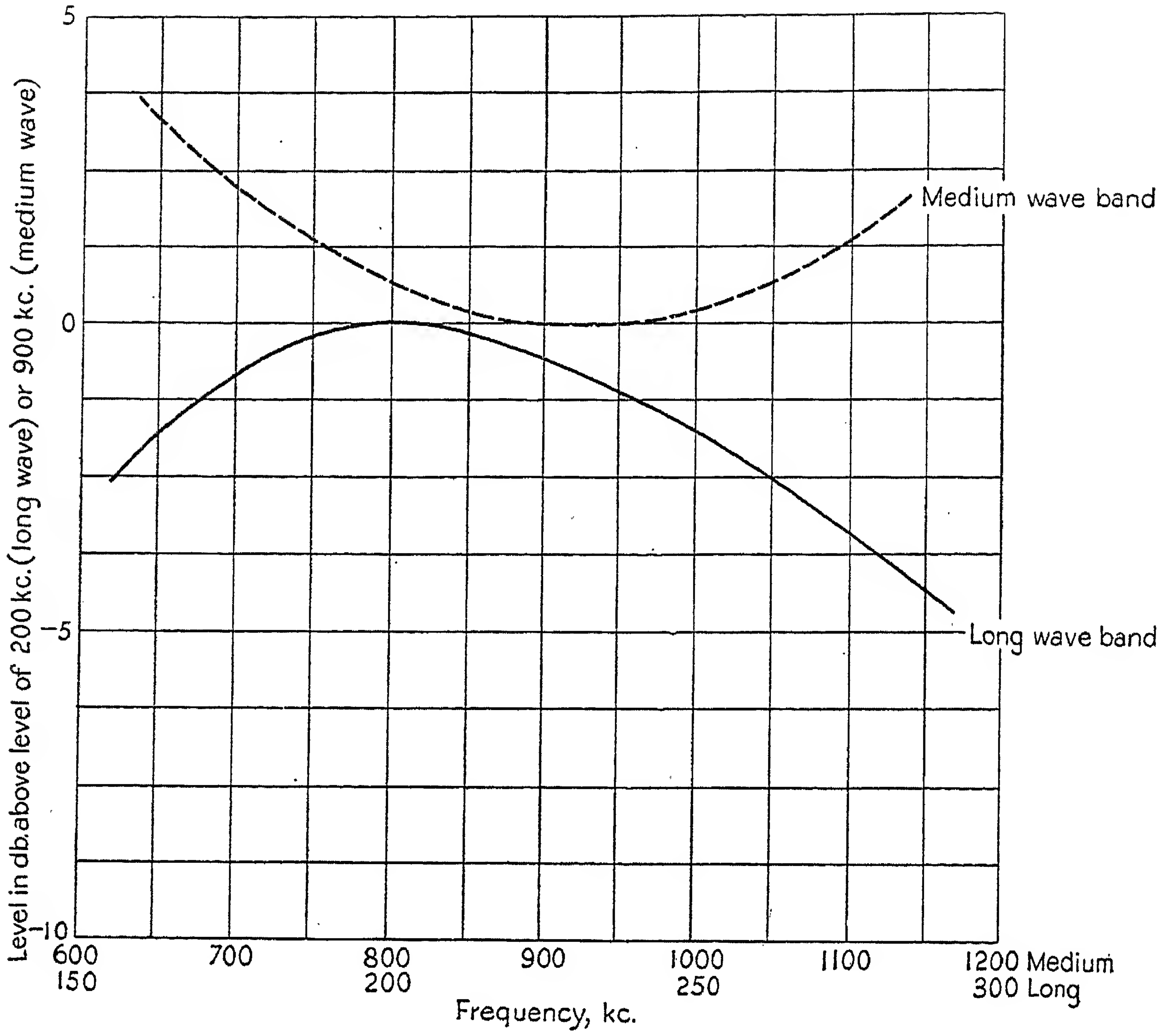

Fig. 7.—Variation of trolley-bus interference with frequency.

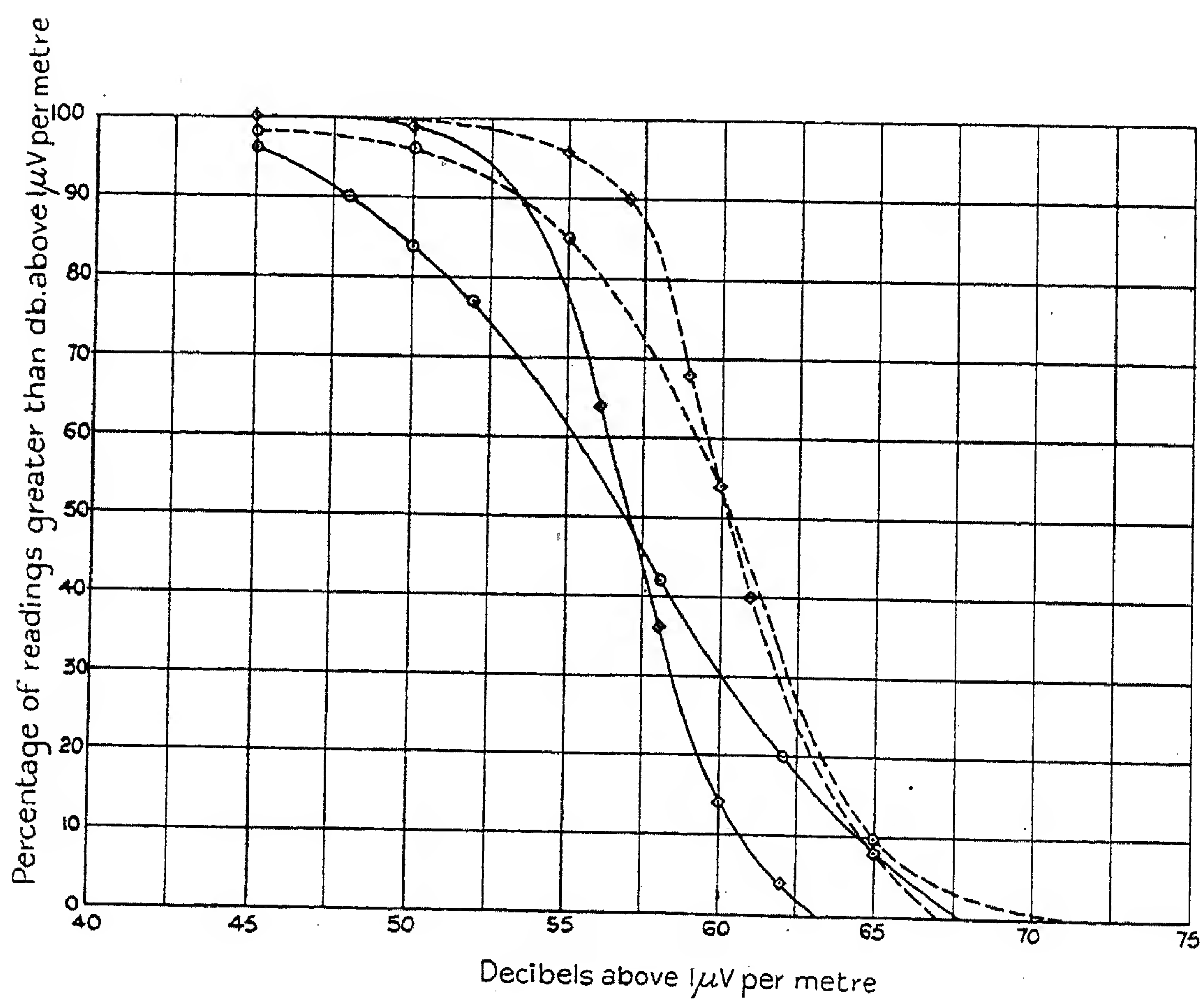

Fig. 8.—Intensity distribution curves of interference level due to trolley-buses. Observation point 10 yd. from track.

A { ——◇——◇—— 200 kc. / — — ◇ — — ◇ —— 900 kc. A. Single bus on a given route.

B { ——o——o—— 200 kc. / — — —o— — — o — 900 kc. B. Normal service.

shows values observed under different conditions for the various sources of interference.

It is observed that, although important where clinch ears are used and for severe conditions such as turning circles, section points, crossings, scaled or ice-coated contact wires, etc., the collector noise has been considerably reduced by the use of lubrication and grooved wires, skid collectors, spring holding devices, and carbon brushes, so that the more frequent and severe interference is due to the operation of contactors and their relay circuits. Motor noise is usually important in special and less frequent circumstances. The noise mainly associated with trolley-buses is therefore of the "click" type, which is not intolerable unless repeated with sufficient frequency. The interference therefore depends upon the traffic density, but it is not usually possible to take this into account until the number of audible "clicks" has been considerably reduced, either by distance (which, for this purpose, should exceed about ¼ mile) or by the application of suppressors.

In order to give an impression of the relative frequency of disturbances of different intensity, Fig. 8 shows an analysis of the distribution of clicks of varying intensity for the representative conditions of a single vehicle on a given route and also of fairly frequent services.

Table 3

Level of Interference from Various Items of a Trolley-Bus Equipment, in db. above 1 μV per metre

Frequency (kc.)	Type of braking	Collectors	Contactors	Main contactors	Main motor	Brake motor	Lighting generator	Distance (yd.)	
300	Rheostatic	73*	73	63	51	43		5	Company A, test track at Town A, line in oxidized and scaled condition
1 200	Rheostatic	75*	71		55	47		5	
300	Regenerative	77*	73		55	43		5	
1 200	Regenerative	73*	74		55	60		5	
1 000	Rheostatic	62†	53		23	5		Under lines	Town B
		63†	54		42	30		3 ft. from bus	
900	Regenerative	29+ } 5 yd.	73		46			Under lines	Town C
200		35+ } 5 yd.	82		54			12 yd. from bus	
900	Regenerative		103		48			12 yd. from bus	Town D
200			75		72			12 yd. from bus	
900	Regenerative and rheostatic							Under lines	Town E
								12 yd. from bus	
200									
900	Regenerative and rheostatic		84		53			do.	
200			78		50				
1 000	Regenerative and rheostatic		74	< 36	38			do.	Town F
200			72	< 36	40				
1 000			76		42	12		do.	Town G
200			72		45	24			
1 000			86	Negligible	18	25	16	do.	H
200			84	< 24	54	45	42	do.	Depot

* Wheel collectors. † Clinch ears and skid collectors.

(ii) High-voltage overhead transmission lines.

The interference arising from high-voltage overhead electric power transmission lines has not been brought so prominently to the notice of the general public as that set up by other agencies, since the greater portion of such lines lie in open country remote from residences. Interference nevertheless arises from such lines and may be conveyed by them from the point of origin to considerable distances and then radiated. In cases where high-voltage lines pass within 1–2 miles of commercial radio receiving stations working on long-distance services the

interference from the lines may be sufficiently serious to prevent the operation of the stations. To some extent this is due to the fact that such commercial stations normally work with a very low value of received signal and are usually placed in positions where electrical interference from other sources is absent.

The interference referred to is generated by the lines or by associated high-voltage switchgear, and can generally be traced to one of the following: arcing at contacts of switches, corona on lines, defective insulators causing corona or arcing.

Fig. 9 shows the frequency distribution over the range 150 kc.–20 Mc. of interfering energy immediately beneath a 132-kV power line at a point where a crackling noise could be heard from an insulator. Although there was no visible indication, even by night, of sparking or corona, continuous crackles were audible 30–40 yd. from the pylon. A series of random square-topped impulses would have given a spectrum in which amplitude was inversely proportional to frequency, but the properties of the line would tend to modify this distribution. It will be noticed, however, that the curve closely approaches this condition at the higher frequencies.

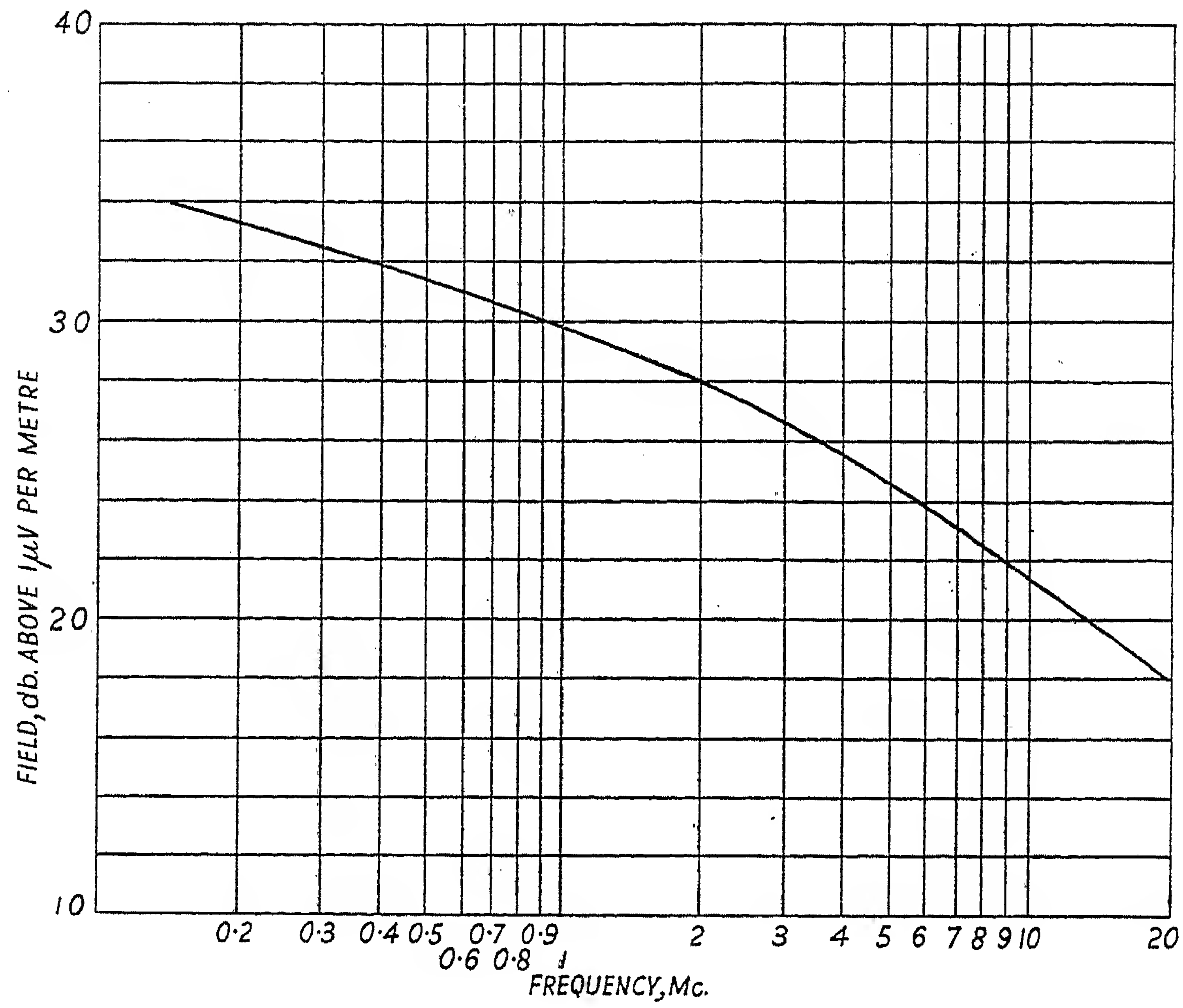

Fig. 9.—Noise field beneath 132-kV power line.

The observed attenuation of the interference on a number of selected frequencies in a direction normal to the power line is indicated in Fig. 10, and suggests that the rate of attenuation per mile decreases with distance. A similar result was obtained in observations of attenuation along the line. Fig. 11 gives the value of disturbing field, at a single frequency of 850 kc., beneath the line at various distances from the source of interference. The rate of attenuation decreases with distance and is much less in this direction than in directions normal to the line. Since the interference is radiated not only directly from the discharging items but also from the line which propagates the interference, the interfering field at any point in the neighbourhood of the system is made up of these component sources of radiation.

The strength of interference from new and clean insulators is of a much lower order of magnitude than that from insulators which have been subjected to weathering. For this reason the results of works tests at normal working voltage on insulators give little indication of the behaviour in service of a line equipped with such insulators.

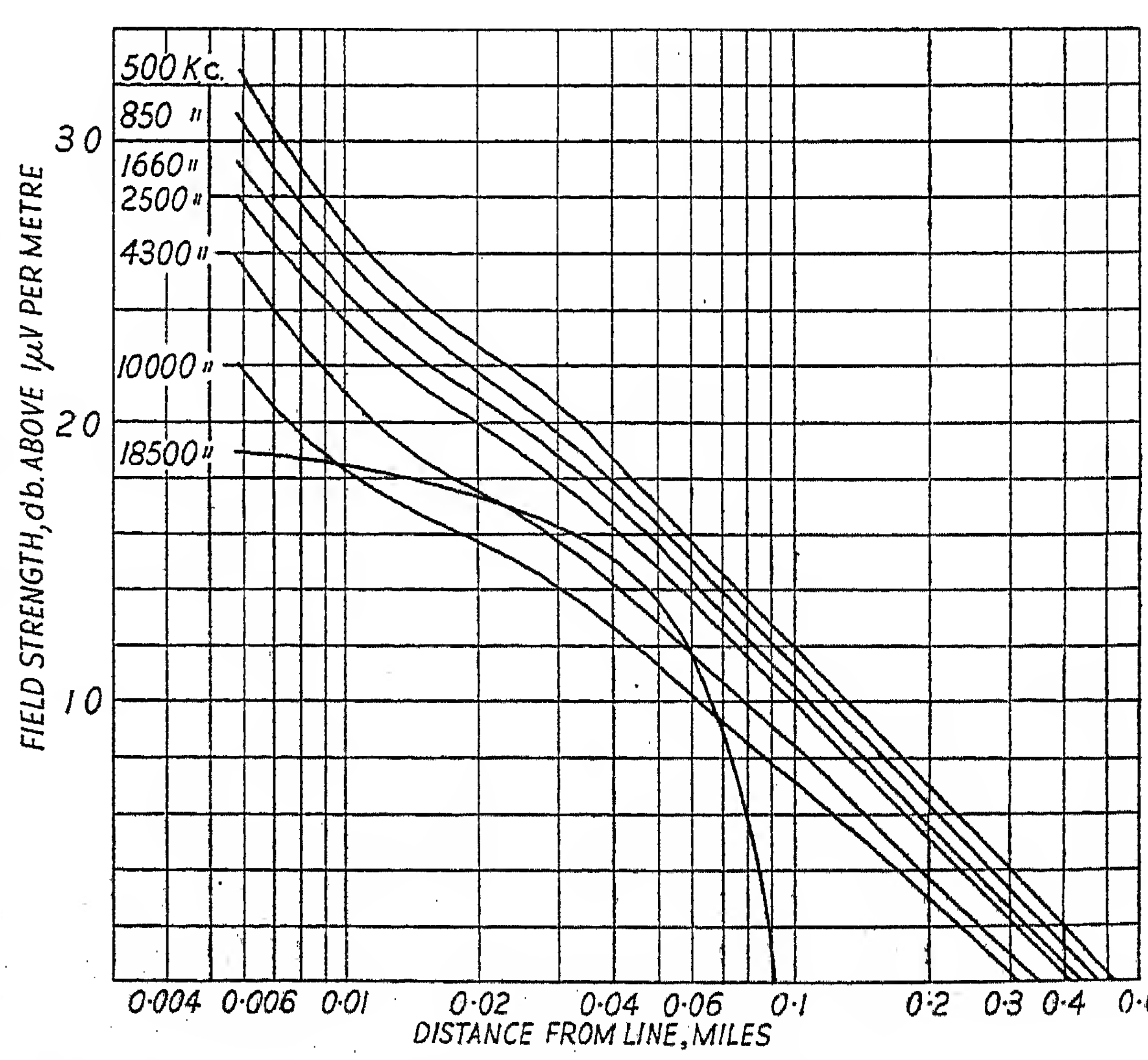

Fig. 10.—Attenuation curves of noise field in a direction normal to 132-kV power line.

In regard to the works testing of insulators, observations taken at the works indicated that the strength of the interference in the short wave band tends to increase

with increase of frequency. The values of interference, in decibels relative to 1 microvolt per metre, from a 3-unit string of insulators tested at 63 000 volts, measured at a distance of 20 yd. from the source of disturbance, were as follows: at a wavelength of 15 m., 14 db.; at 20 m., 14 db.; at 30 m., 12 db.; at 40 m., 12 db.; at 60 m., 14 db.; at 80 m., 10 db.

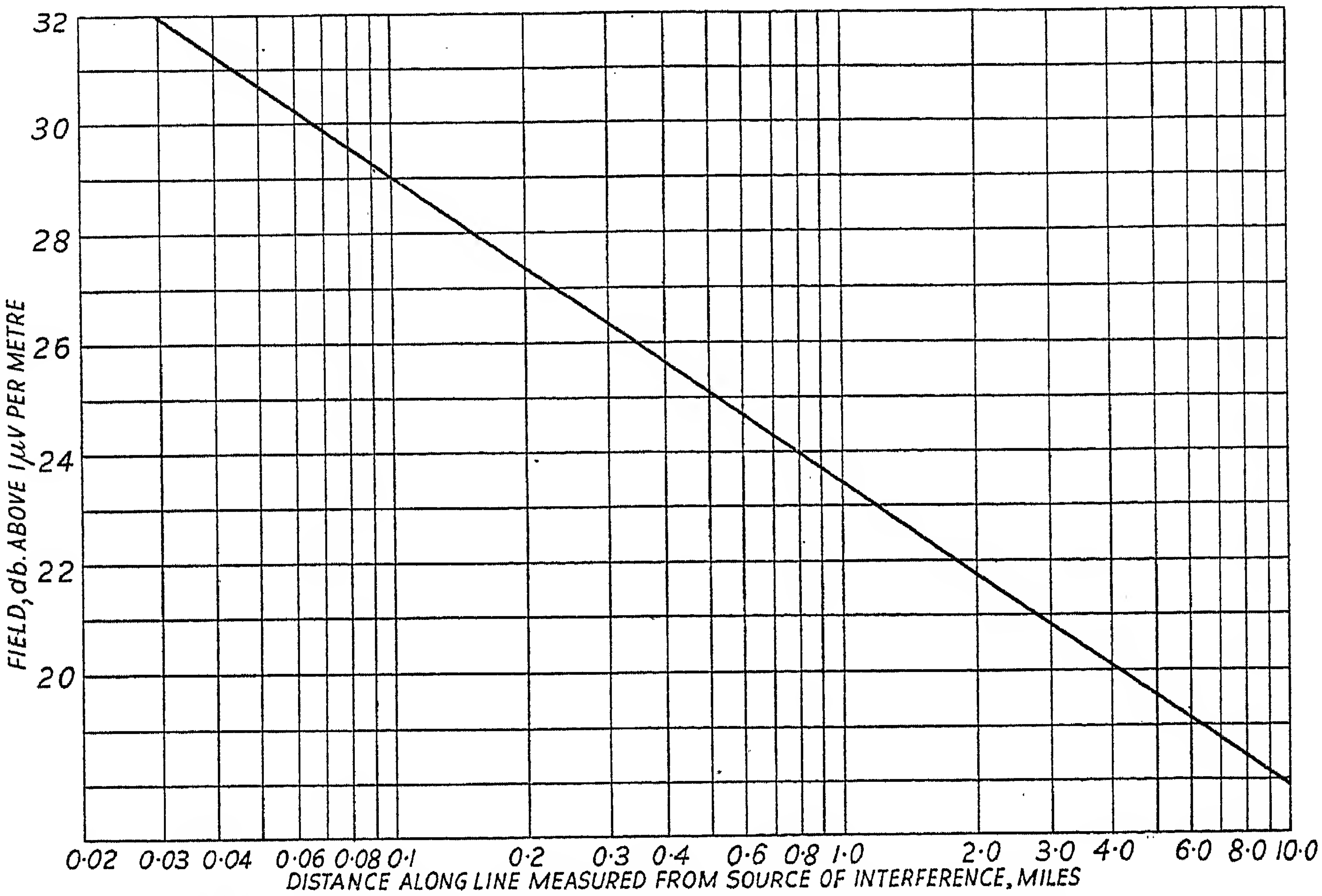

Fig. 11.—Field strength of noise beneath 132-kV power line on 850 kc.

For lines equipped with similar types of suspension and cap-and-pin insulators the strength of the interference appears to be independent of the line voltage of the system. The effect of weather conditions on the interference from a line is exemplified by Table 4, which gives the values measured at a distance of 15 yd. from a 132-kV line under wet and dry conditions respectively.

Table 4

Wavelength (m.)	Interference level (db. above 1 μV per metre)	
	Dry condition	Wet condition
15	— 16	2
20	— 12	8
200	16	42
350	20	46
1 550	28	56
2 000	30	58

In Germany, insulators are tested in the factory by observing the h.f. interfering current which flows when the insulator, under an appropriate applied voltage, is short-circuited by a condenser. This method depends upon the assumption that the impedance of the overhead line is small compared with the effective h.f. impedance of the insulator when causing interference in service.

(iii) High-frequency apparatus.

An obvious source of interference is apparatus which generates and utilizes h.f. currents, such as h.f. medical and surgical equipment (e.g. electrotherapy and diathermy), and h.f. furnaces. The radiation becomes greater as the working wavelength of the apparatus is reduced and as the dimensions of unscreened portions of the circuits approach the order of magnitude of the wavelength.

The most common source of interference of this class is electromedical apparatus, which includes equipments of moderate or high power used under professional supervision for therapy and diathermy and also the smaller portable equipment known as "violet-ray apparatus." The fundamental difference between electrotherapy and diathermy is that in the former there is no conductive connection between the apparatus and the patient, energy being conveyed through the capacitance of air-gaps, while in the latter there is a conductive connection between the apparatus and the patient. In both types of equipment h.f. currents are generated, either in the form of damped waves by a simple type of spark transmitter circuit or by the use of thermionic valves energizing an oscillatory circuit. The output h.f. voltage in each case is stepped up to a high value by means of a transformer and then applied to the patient by means of either one or two electrodes.

When a single electrode is employed, as in the case of the small portable type of violet-ray apparatus, the secondary currents return via earth capacitances, and intense radiation at high frequencies occurs. With electrotherapy and diathermy apparatus, however, two electrodes are employed and the secondary circuit consists of a smaller loop than in the single-electrode case. In consequence the field directly radiated may not be quite so severe. It is found, however, that the field around the apparatus, patient, and connecting leads will

still be sufficiently intense to interfere seriously with radio reception.

The mains-borne interference from both types of plant will always be serious and may be propagated along the supply mains for several hundreds of yards. As such apparatus is frequently installed and used in residential districts, it may thus become a source of interference to radio listeners over a wide area.

In general, interference set up by this type of plant will be more or less tunable and will have a maximum at the frequency of generation. A large proportion of the equipments at present in use operate on the long- and medium-wave broadcast bands. Some of the latest types of apparatus which are coming into general use in this country are capable, however, of interfering very seriously with the reception of television on ultra-short wavelengths, and the range of this interference may be as much as 5 miles. Cases have been reported of interference in this country on short wavelengths between 10 and 100 m. From the fact that this interference had a pronounced 60-cycle modulation, it has been assumed that it was caused by electromedical apparatus in America.

Particulars of the levels of interference from therapy and diathermy plant on long and medium waves are given in Section (3) (*a*) (vi). Tests have been made by the E.R.A. as regards ultra-short waves on the following therapy and diathermy plant: (1) 0·5-kV 30-m. valve generator, (2) 0·3-kV valve generator (30 and 6 m.), (3) spark machine (15 to 6 m.), (4) spark machine (300 m.). An artificial load consisting of a wooden block or a dish of solution was used, and the field strength measured by the short-wave receiver mounted in a van.

The valve machines emitted radiation only at the fundamental and harmonic frequencies. Fig. 12 shows the variation with distance of the field due to the harmonics of Machine (1). The associated noise was small owing to the use of rectified and smoothed H.T. supply to the valves, the a.c. supply leads being also fitted with h.f. chokes. Machine (2) was supplied with raw alternating current and consequently the field produced was heavily modulated; metal panels were fitted to the machine but were not bonded and had apparently little screening effect. The removal of the leads to the patient reduced the radiation by about 10 db. at a fundamental frequency of 42·5 Mc. The variation of the field of fundamental frequency with distance is shown in Curve A, Fig. 13, while Curves B, C, and D refer to the 3rd, 4th, and 5th harmonics respectively, when a lower fundamental frequency (7·6 Mc.) was used. The band width of the radiation on the fundamental and harmonics of both valve machines varied from 500 to 150 kc. when referred to a level 40 db. below the maximum, and measured with the short-wave measuring set already described. The field from Machine (3) at 37·4 Mc. is shown in Fig. 14. With this machine the patient forms a part of the output tuned circuit. As opposed to valve machines, spark machines emit radiation over a wide band of frequencies. For Machines (3) and (4), Fig. 15 shows the radiation to be distributed over the band from 20 to 50 Mc.

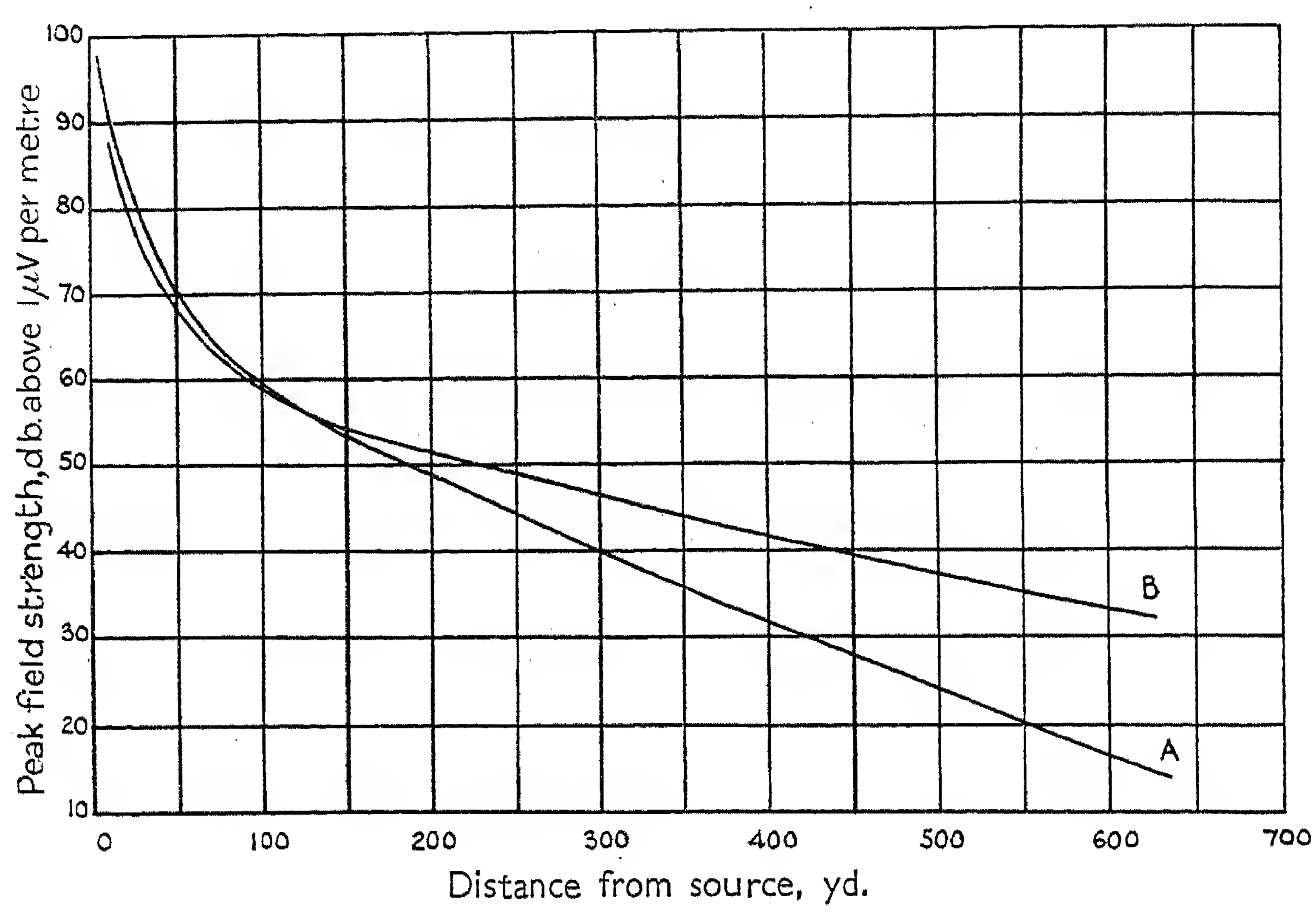

Fig. 12.—Variation, with distance from source, of radiation field given by 30-metre 0·5-kW valve therapy machine. Output current, 2 A.

A. 2nd harmonic (24 Mc.).
B. 4th harmonic (48 Mc.).

It is obvious from these results that h.f. therapy machines of such types are capable of causing serious interference to television reception over a considerable area, on both the fundamental frequency and the harmonics of valve machines and over the whole band in the case of spark machines.

(iv) Electric lifts.

The equipment of a lift comprises interfering items in the form of the driving motor, giving continuous noises, and of the contactor relay and control circuits, which give noises of the "click" type. This equipment is often installed in buildings (and ships) where radio receivers

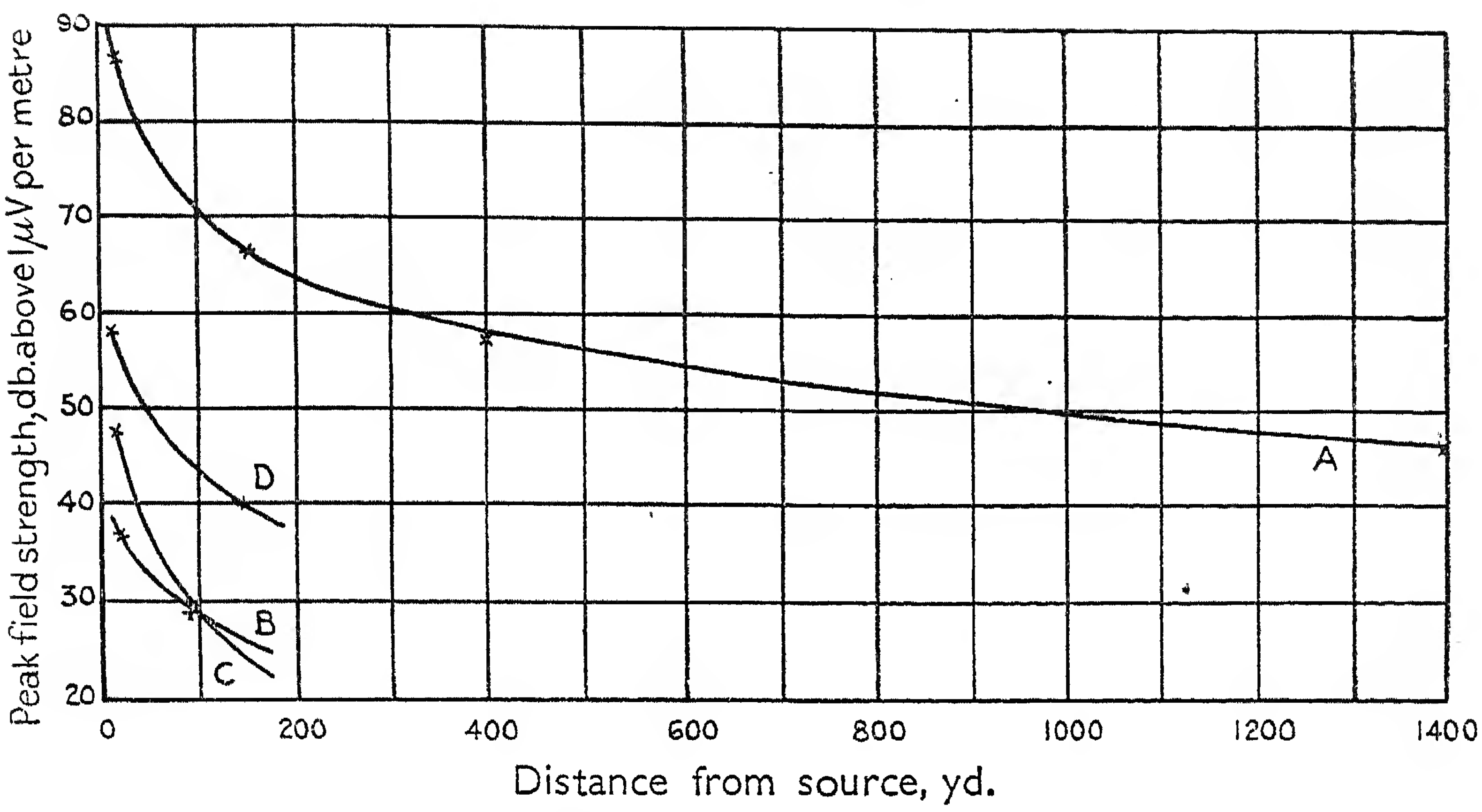

Fig. 13.—Variation, with distance from source, of radiation field given by 30–6 metre 0·3-kW valve therapy machine. Output current, 4 A.

A. Fundamental of 42·5 Mc.
B. 3rd harmonic of 7·6-Mc. fundamental.
C. 4th harmonic of 7·6-Mc. fundamental.
D. 5th harmonic of 7·6-Mc. fundamental.

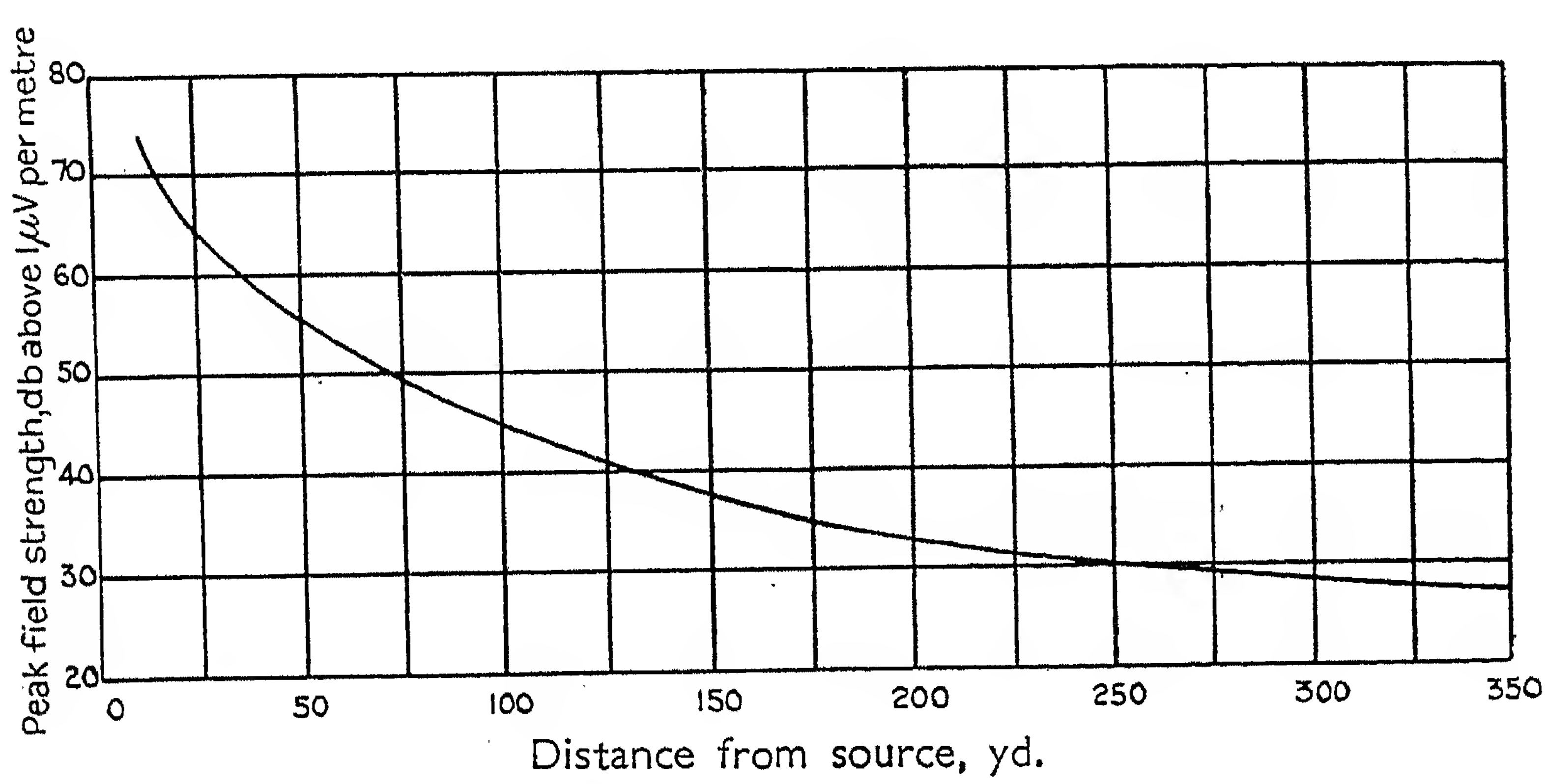

Fig. 14.—Variation, with distance from source, of radiation field given by 6–15 metre spark therapy machine. Frequency 37·4 Mc., output current 2 A.

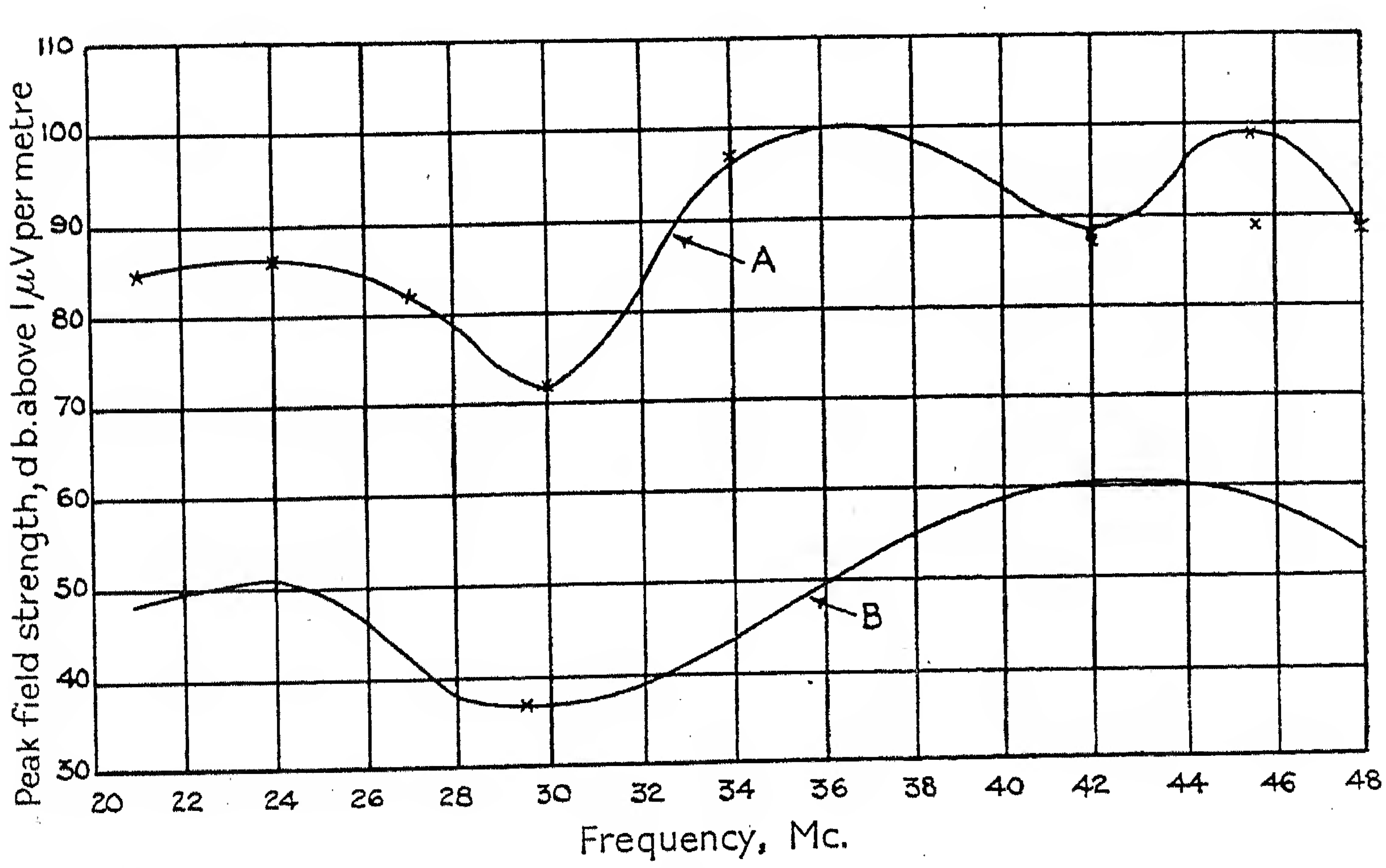

Fig. 15.—Frequency variation of intensity of radiation for spark machines.

A. 30–6 metre spark machine, output current tuned to 37 Mc.
B. 300-metre spark machine.

operate in close proximity. The radiation is further increased by the fact that the interfering sources are connected or may be coupled to the trailing cable which connects the panel in the lift car to the main equipment, and to the wiring between the gate interlocks, switches, etc., and the control gear and supply. Whereas the latter wiring is often run in steel conduits the trailing flexible cable is suspended between the car and the half-way box, normally without metallic protection. A schematic diagram is shown in Fig. 16.

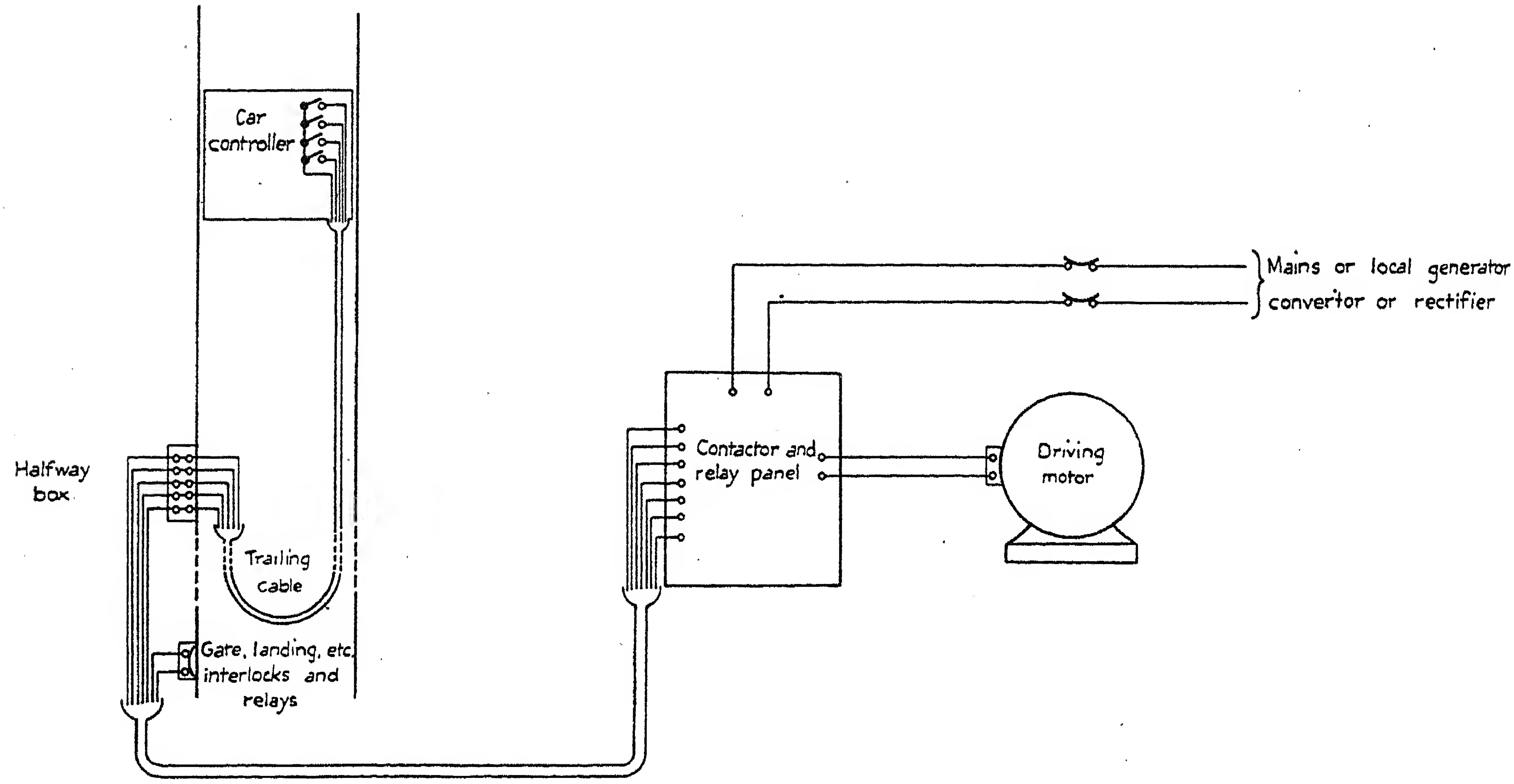

Fig. 16.—Simplified circuit scheme for lifts.

Interference may thus reach the listener's receiver by way of the electric mains, if on the same system as the normal domestic services, or by direct radiation from the motor and main control gear, from wiring in the shaft or from the trailing cable acting as a radiating aerial. In addition, it sometimes occurs that the lift shaft is wholly or partly enclosed by a metal network, which may be inadequately earthed from an h.f. point of view. H.F. voltages may then be developed along the shaft which, although small, can give serious interference since the coupling with the listener's aerial may be high. Tests made on a lift partially enclosed by wire netting yielded voltages of the order of 1 mV developed therein between the halfway level and earth. This value could be considerably reduced by efficient earthing of metalwork.

The radiated motor interference is less than that due to the control circuits, for well-maintained motors. The "motor noise" is negligible for lifts operated on motor-generator systems, while for d.c. motors with direct supply the noise is generally at least 10 db. below the level of other disturbances, except where faulty commutation or other defects cause a high interference value. Auxiliary motors for automatic gate-closing must also be considered, but follow the same principles as for other small motors. Control circuits energized with alternating current, as in some modern types of lift, cause little disturbance. The main interference is due to the circuits controlling the operating coils of the contactors and switches of the driving motor and also the brake-magnet coil. These circuits ascend the shaft and are operated by hand or automatically in the car or at the gates. They are most troublesome when supplied direct from the mains, being then usually highly inductive. In some older types of lift, the manual control circuits carry the holding, closing, or tripping currents and are then a source of severe interference. In general, all the circuits for remote control, particularly those which enter the trailing cable, form systems which give an h.f. radiation, determined by the inductance of the coils and the self-capacitance of the circuit involved.

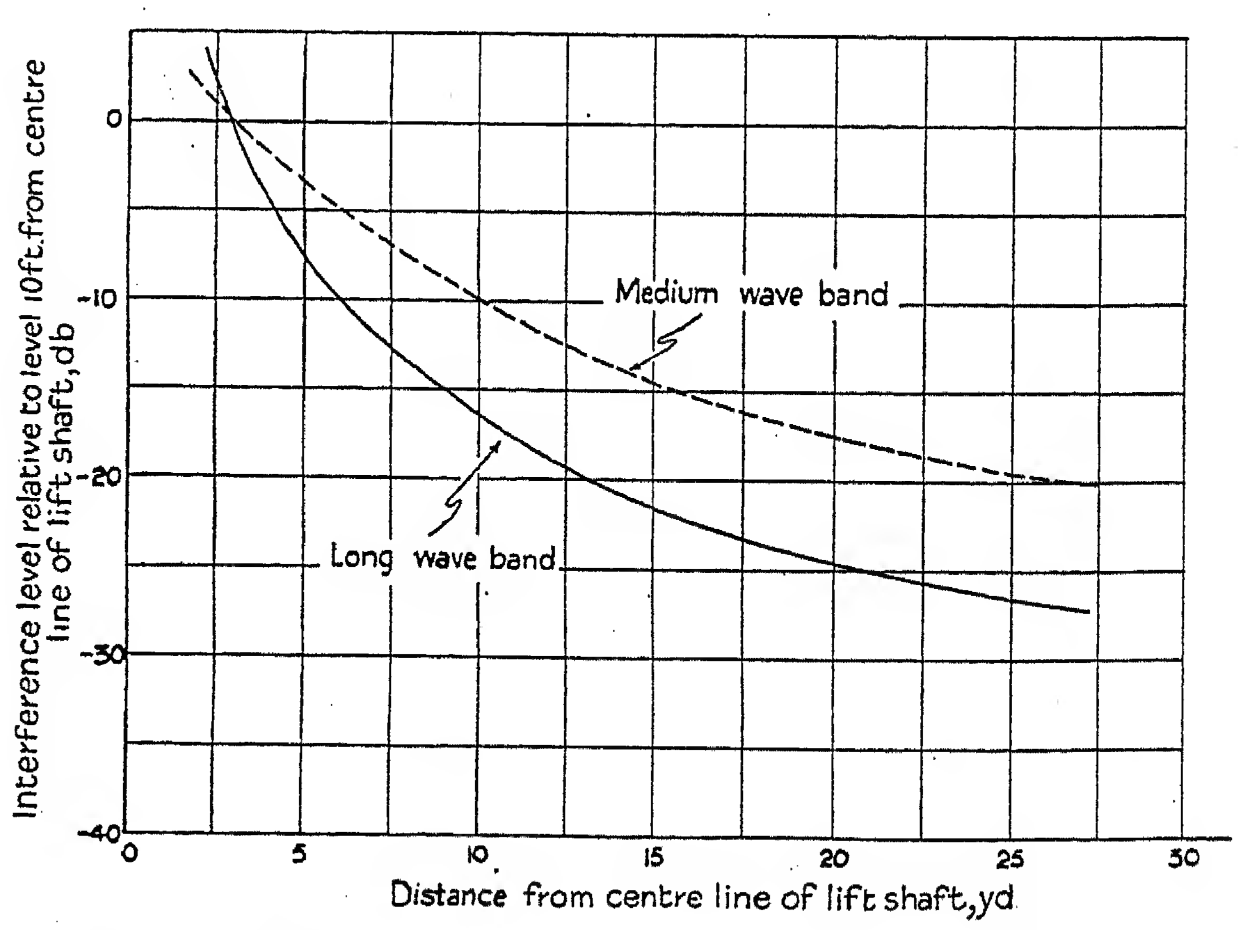

Fig. 17.—Variation of interference with distance from centre line of lift shaft.

The brake-magnet coil is also a radiating source,

although its current is confined to the main installation. The other heavy-current circuits such as those associated with the motor do not usually radiate much interference on closing or interruption. Tests in which these circuits were manually operated showed that their effect might be neglected in comparison with that of the control circuits, at least at distances greater than about 10–20 ft. from the main installation.

Table 5 shows values of the field due to some representative types of lift. Some figures indicating the rapidity of attenuation with distance from the lift are given in Fig. 17. The variation of interference with frequency is not marked.

Table 5

UNSUPPRESSED LEVEL OF RADIATED INTERFERENCE FROM ELECTRIC LIFTS

Lift No.	Type of car contro	Control-circuit supply	Distance of test position from trailing cables (ft.)	Average interference level (db. above 1 μV per metre)			
				900 kc.	1 000 kc.	190 kc.	180 kc.
1	Hand-driven controller, direct control	D.C.	10	77–65	—	—	62–53
2	Push-button remote control ..	D.C.	10	45	—	—	30
3	Push-button remote control ..	A.C. supply, a.c.–d.c. motor-generator	10	28	—	—	40
4	Hand-driven controller	D.C.	10	—	30	39	—
5	Push button	D.C.	10	—	37	34	—
6	Push button	A.C. supply rectified by mercury-arc rectifier	10	—	44	52	—

(v) Telecommunication apparatus.

Telecommunication apparatus can, in certain circumstances, give rise to radio interference. In the case of automatic telephone plant the interference may be caused by plant at the exchange or at the subscriber's premises. In the exchange the numerous relays and selectors constitute a source of interference, although this is greatly reduced by the present practice of fitting spark-quench circuits to apparatus for the preservation of contacts. When underground distribution is employed, little or no interference occurs except in the immediate vicinity of the exchange building and this can generally be relieved by re-positioning the listener's aerial. Where overhead distribution is used the interference can be troublesome, and in view of the multitude of switching contacts concerned it is usually more economical to filter all circuits leaving the exchange building than to apply filters to all sources of interference within the building. Table 6 gives the interference from a small exchange measured at a point 15 yd. from the exchange building.

The fitting of filters at the exchange building does not eliminate the interference produced by the subscriber's own dial. This interference, however, is only likely to affect receivers in the immediate vicinity of the subscriber's instrument and line. It can readily be eliminated where troublesome by fitting a dial suppressor.

Machine telegraph apparatus is also a potential source of interference, but the number of cases where such interference is troublesome is relatively small as the apparatus and circuits are not normally present in areas where broadcast reception is prevalent. Moreover, apart from direct radiation, which is of comparatively short range, the trouble is usually caused by radiation from overhead lines, which are rarely employed in areas where machine telegraphs are installed. The chief difficulty arises with such equipment when it is installed inside a radio-telegraph receiving station handling long-range traffic. Here the interference can be sufficiently great in relation to the average signals to embarrass the service.

Table 6

Frequency (kc.)	Signal (db. above 1 μV per metre)	Noise (db. above 1 μV per metre)		Signal/noise ratio (db.)	
		Before suppression	After suppression	Before suppression	After suppression
877 (London Regional)	34	42	− 8	− 8	+ 42
200 (Droitwich)	63	23	+ 2	+ 40	+ 61

(vi) Ignition systems.

Although installations such as oil-burning furnaces

comprise ignition systems which may give rise to appreciable interference, the motor-car is so eminently the most widespread example that it deserves special study. Both the low-voltage equipment and the high-voltage circuits form radiating systems.

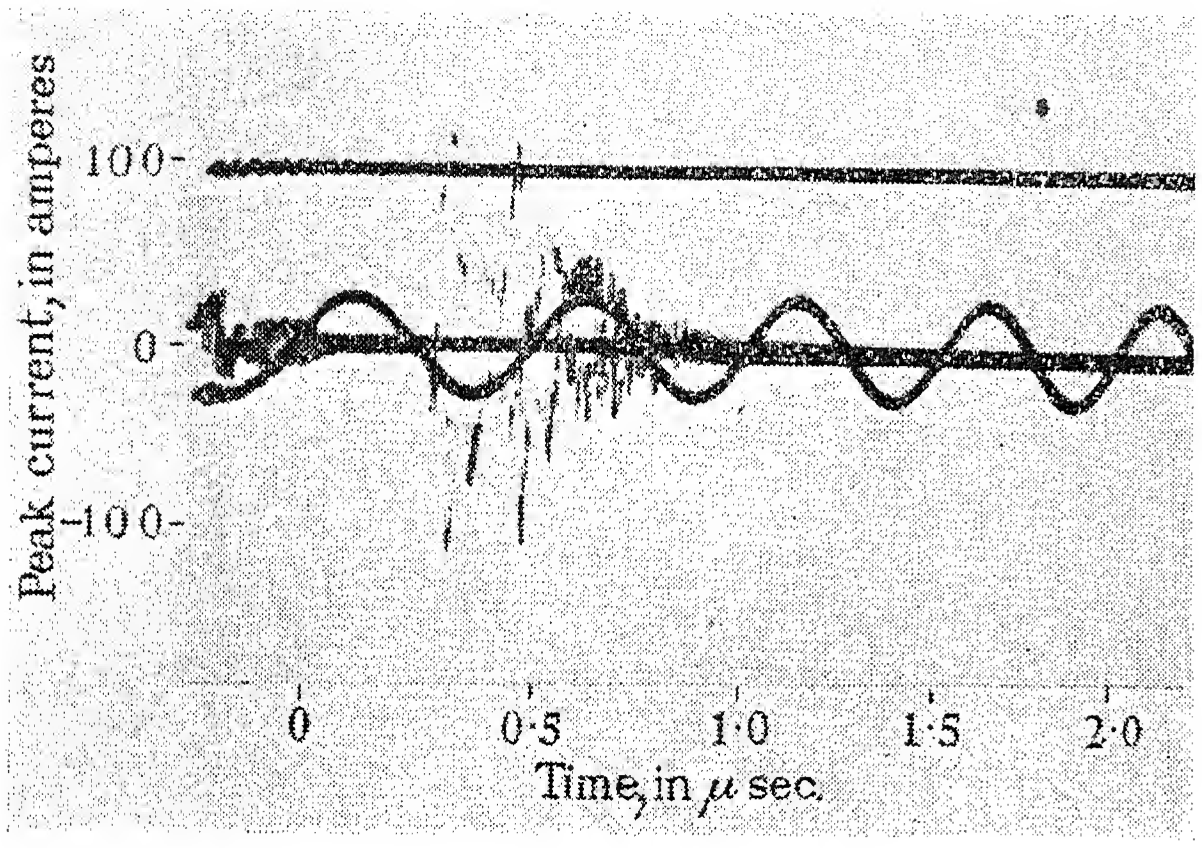

Fig. 18.—Oscillatory spark currents.

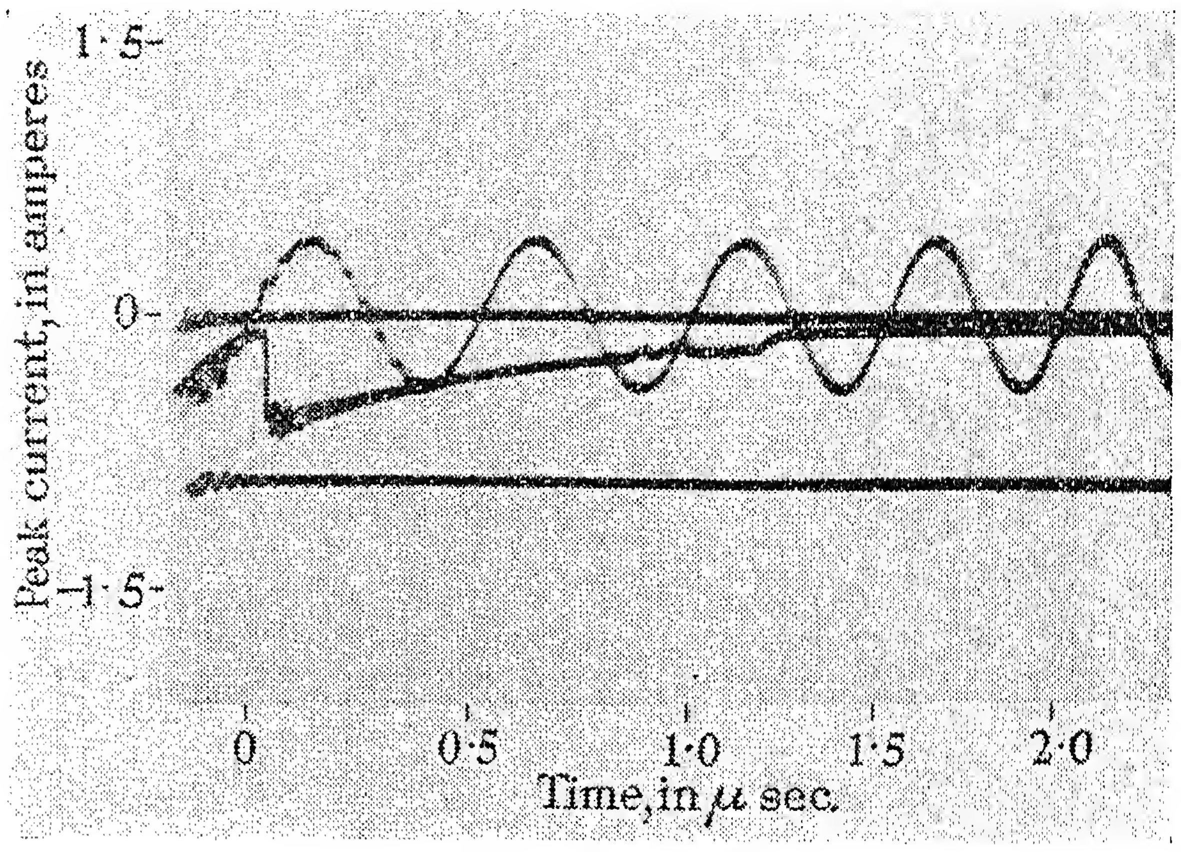

Fig. 19.—Non-oscillatory spark currents (10 000 Ω resistor in plug lead.)

In the latter, the circuit formed by the plug, plug lead, distributor, coil or magneto, and chassis, is excited by the discharge at the plug and the spark at the distributor (if a jump-spark distributor is used), giving rise to a train of very high-frequency damped waves repeated at each discharge, as shown in Fig. 18.* The current may attain instantaneous values of the order of 100 amp. If resistance is present, as when a suppressor is inserted at the plug (see Fig. 19*), the current transient becomes non-oscillatory and of very steep wave-front, but the crest value is very much reduced. These rapid transients are succeeded by oscillations of longer period. The radiation extends over a wide frequency-range. The lower frequencies, covering the lower-frequency broadcast bands, appear to be determined by the inductive discharge of the coil or magneto. The effective inductance of the latter with the self-capacitance of the circuit gives an oscillation spectrum, similar to a circuit with distributed constants subject to shock excitation. From the interference point of view, the higher frequencies, particularly the range 10–80 Mc., are more important, since the radiation is more intense and the services envisaged for this band are of lower field-strength. At these frequencies it appears that the alternating components of the initial disturbance are radiated from the distributor and plug leads, which act as aerials. The audio-frequency response thereby produced in a receiver is a series of impulses of which the time of passage is of the order of 3 millisec., which is much less than the interval between successive impulses, this interval being that between successive sparks.

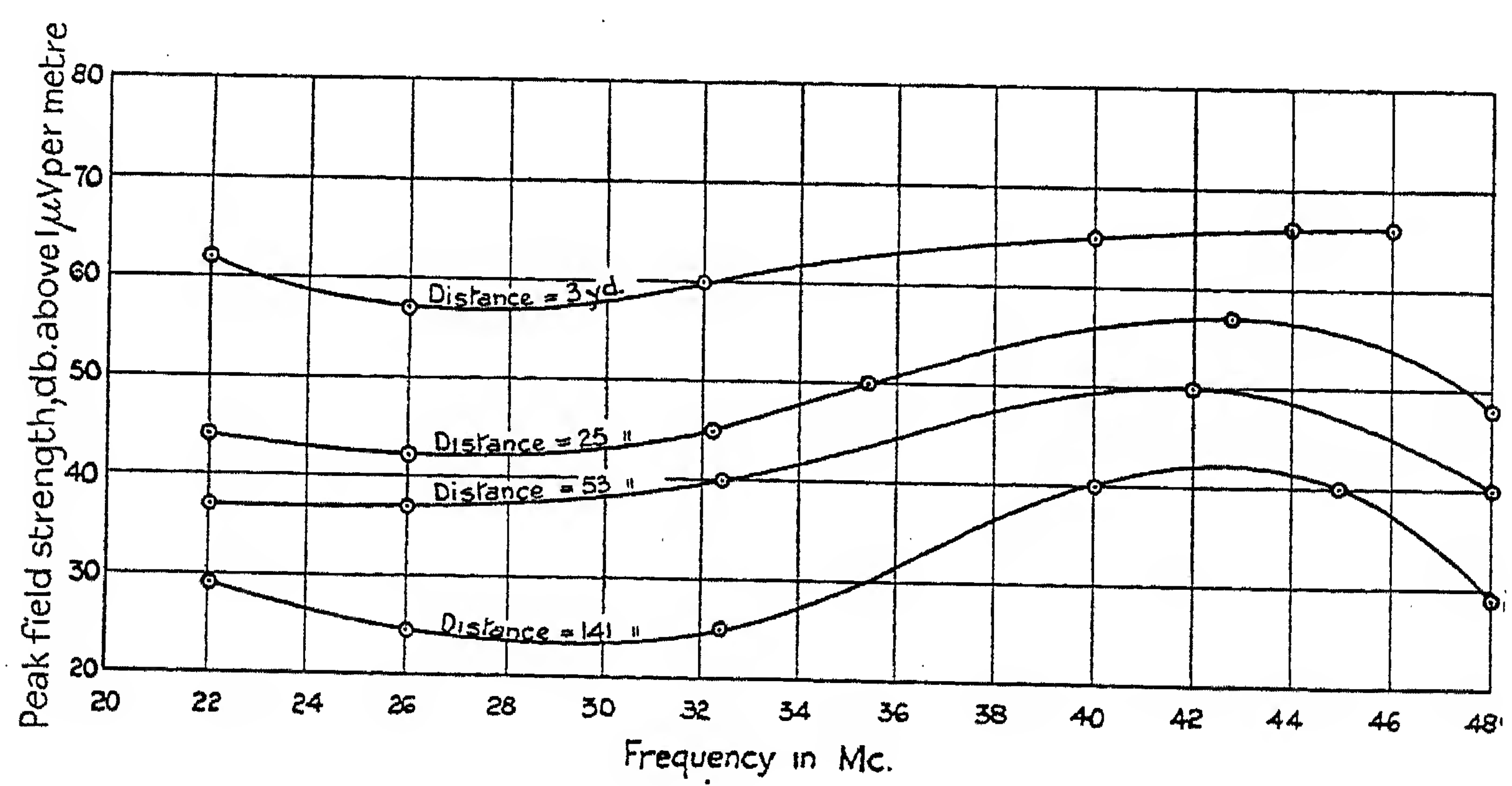

Fig. 20.—Frequency variation of average peak field-strength of interference from automobiles. Values obtained on Western Avenue.

Fig. 20 shows the variation of interference with frequency observed near an arterial road, and Fig. 22 shows the attenuation with distance. The order of levels observed and their relatively slow attenuation with distance indicate that motor-cars must be regarded as important potential interfering sources. Fig. 21 shows

* Oscillograms obtained by W. Nethercot, of the E.R.A., on discharges in air at normal temperatures and pressures.

the results of tests on a number of automobiles at a standard distance of 10 yd. (ground level) and a standard speed of 30 m.p.h. For a level of 50 μV per metre (provisionally adopted) no correction is usually required

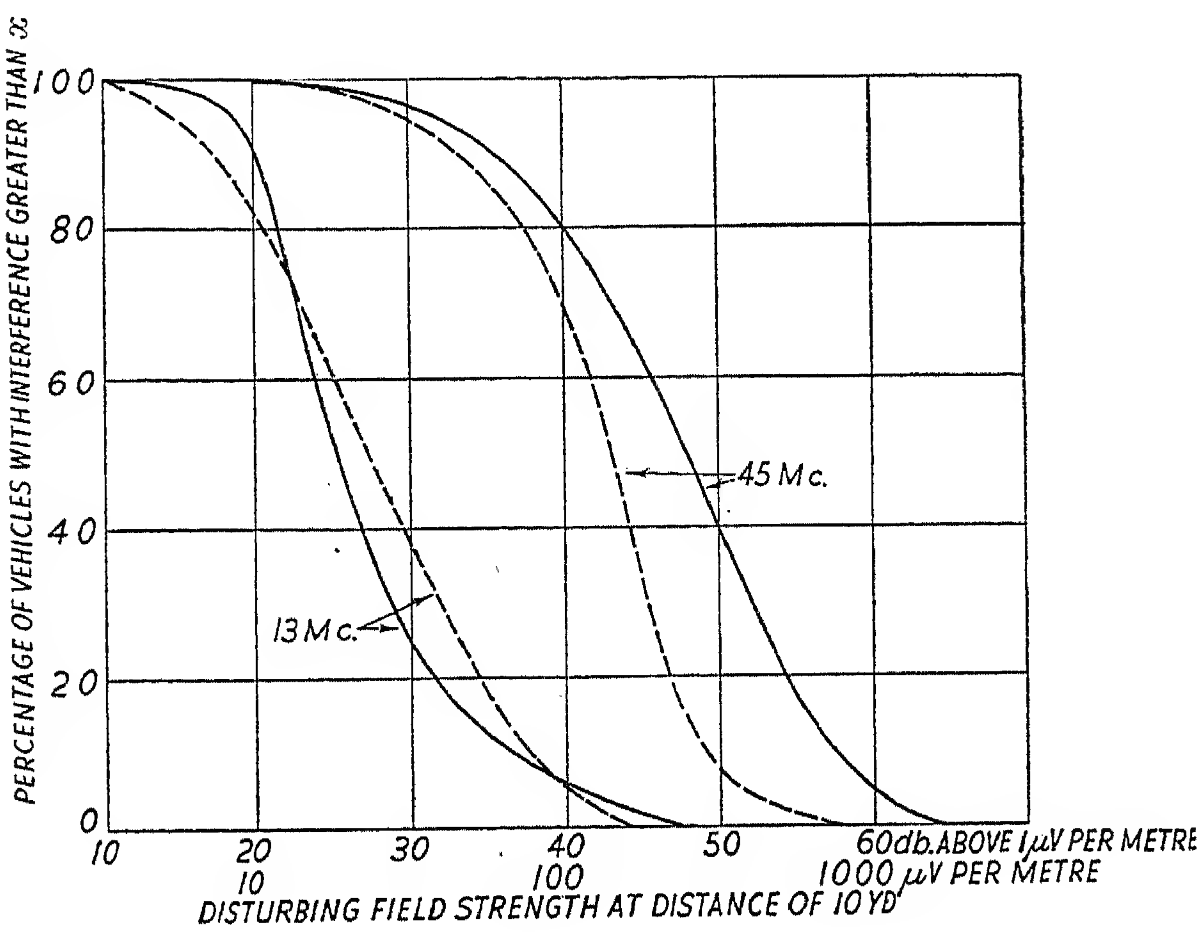

Fig. 21.—Interference due to automobiles.

——— Private cars.
– – – – Commercial vehicles.

at 13 Mc. and only about 15 db. at 45 Mc. All the systems considered later are capable of giving suppression of this order, so that automobiles suppressed for receivers mounted thereon will also be suppressed as regards external receivers. It is common in modern cars to mount the coil on the bodywork, and this practice gives a long distributor lead. Recent E.R.A. tests have shown that if the coil is suitably mounted on the engine so as to reduce the dimensions of the radiating circuit and confine it to the engine, the interference levels just quoted may be reduced by 8–21 db. By redesign of the layout on this and similar bases it is possible in some cases to avoid the necessity for the use of actual suppressors.

The lower-frequency radiation from the high-voltage circuits and the radiation from the low-voltage equipment is mainly of importance with respect to receivers in the vehicle. As regards the low-voltage equipment, it may be mentioned that auxiliaries such as voltage regulators and windscreen wipers are frequently the most severe sources of disturbance. The disturbance is radiated from the car wiring as a whole and, though intense in its immediate neighbourhood, is rapidly attenuated with distance.

(b) Re-radiated Interference

(i) Domestic items.

The increasing use of electrical appliances for domestic purposes has brought the question of interference prominently to the notice of the large mass of the general public, as the source of interference is in their own homes or in adjacent premises and the disturbance from this class of plant is concerned almost solely with reception of broadcast programmes. The sources of interference can be divided broadly into two groups, namely motors and switching devices. Some types of equipment contain both sources of interference, e.g. electric refrigerators using commutator motors. The normal path of interference is from the interfering item via the supply mains to the vicinity of the receiving aerial, whence it is radiated from unscreened portions of the wiring and picked up by the aerial-earth circuit of the receiver. The amount of interference created by such devices will depend on the interference voltage set up by the appliance, the internal impedance of the appliance to the h.f. disturbance, and the attenuation in the path between the device and the receiving antenna. The interfering device can be regarded as a radio-frequency generator with a definite internal impedance supplying energy to the mains.

Owing to the fact that some countries already had legislation requiring the suppression of interference in such devices, it became necessary to attempt to secure

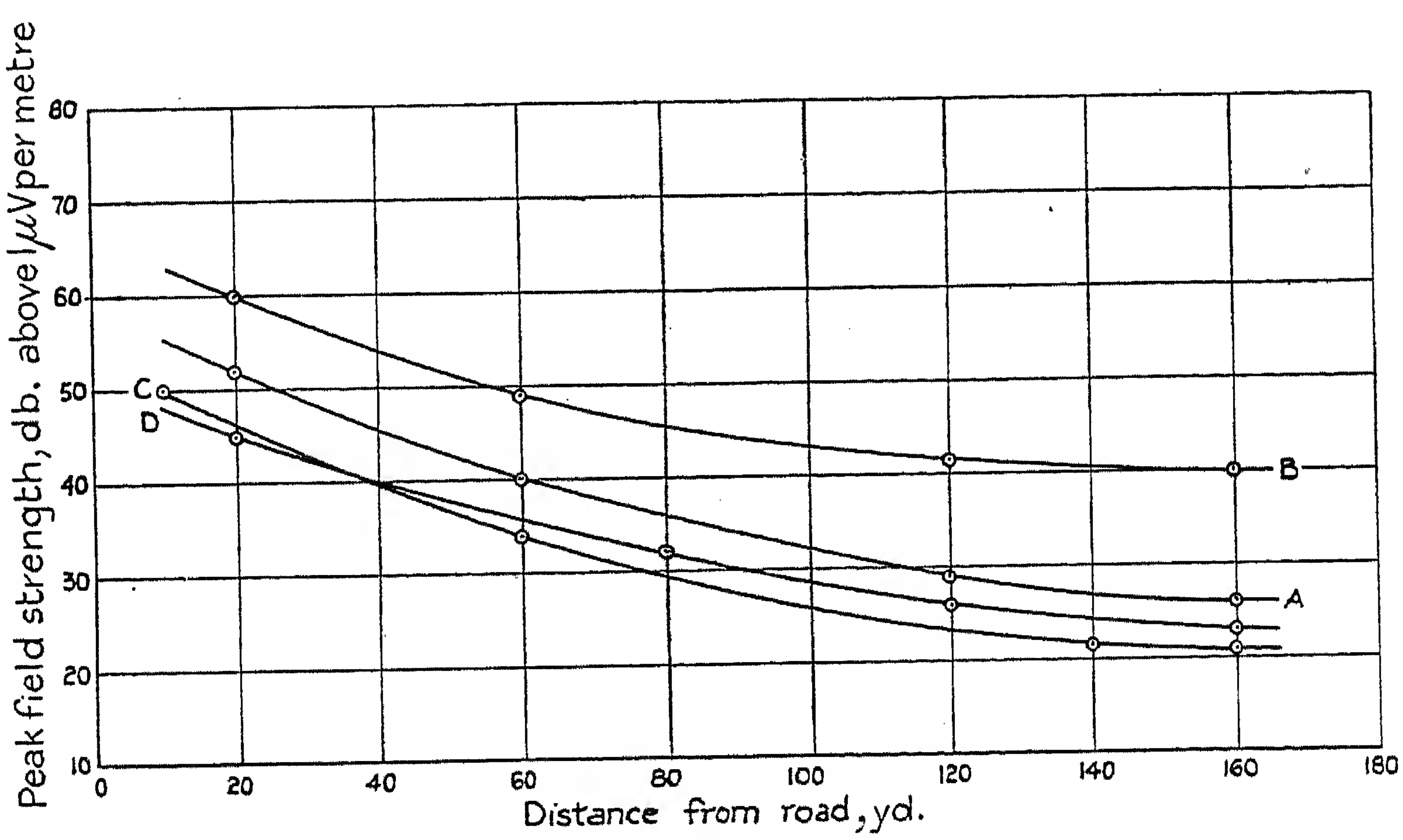

Fig. 22.—Variation of average peak field-strength of interference from automobiles, with distance from road. Values obtained on Western Avenue.

A. Frequency = 48 Mc.
B. Frequency = 45·5 Mc.
C. Frequency = 26·0 Mc.
D. Frequency = 21·0 Mc.

international agreement as to the value of noise voltage which could be tolerated in such plant. With this object in view the I.E.C. appointed in 1934 a Special International Committee on Electrical Interference (C.I.S.P.R.) to study the subject. In connection with the work of this Committee a number of measurements have been made in this country of the interference voltage generated by domestic and other low-power appliances. Measurements have also been made of the effective heights of listeners' aerials, the coupling between the receiving aerial and the mains, and the impedance of the latter.

For the purpose of the measurements the effective height of an aerial was defined as the ratio between the e.m.f. measured on open circuit across the aerial and earth terminals of the receiver in its usual situation and the value of e.m.f. which would be obtained with an aerial of an effective height of 1 m. placed in a free position outside the listener's premises.

The coupling between the receiving aerial and the interfering item was determined by the application of a sinusoidal h.f. voltage of known value symmetrically and asymmetrically between the mains terminals of the interfering apparatus, and between these terminals and earth, by means of a portable calibrated generator substituted for the machine or apparatus, and the measurement of the open-circuit e.m.f. induced between the aerial and earth terminals of the receiver. It was also decided to adopt a value of the order of 1 volt for the voltage applied to the mains, in order to reduce errors which might be caused by the presence of other noises.

The British measurements were carried out by the G.P.O. and were made at the houses of 214 listeners. Of the premises visited, 40 % were those of members of the staff of the Post Office Engineering Department at Rugby, Baldock, St. Albans, and N.W. London, 5 % were those of officers of the B.B.C., 20 % were those of members of the general public who had complained of electrical interference with broadcast reception, and the remainder were those of members of the general public who agreed to measurements being made on being told of the nature of the experiments. Such members were selected at random from districts which were as far as possible uniformly distributed over London. Post Office field-strength measuring sets of the type shown in Fig. 2 were utilized for measuring the voltage developed between the earth and aerial terminals at the listener's premises by the insertion of a high resistance in series with the normal aerial input connection of the measuring set to increase the input impedance of the set; the e.m.f. to be measured being applied between the remote end of the resistance and the casing of the set. Sets modified in this manner have been found convenient for the measurement of the effective height of receiving aerials, the set being used first as a voltmeter for measuring the voltage induced in the antenna by a broadcast transmission and then as a field-strength measuring set. The ratio of the signal thus measured, in microvolts (open circuit), to the field strength of the radiation in free space near the antenna, in microvolts per metre, gives the equivalent effective height in metres. The measurements were made on frequencies of 200, 876, and 1 150 kc.

A summary of the data obtained regarding effective heights of aerials is given in Fig. 23. The probable accuracy of the measurements is estimated as $\pm$ 2 db. (approximately $\pm$ 20 %). It was found during the tests that the proportion of listeners using outdoor aerials was 70 %. Analysis of data curves of the effective heights

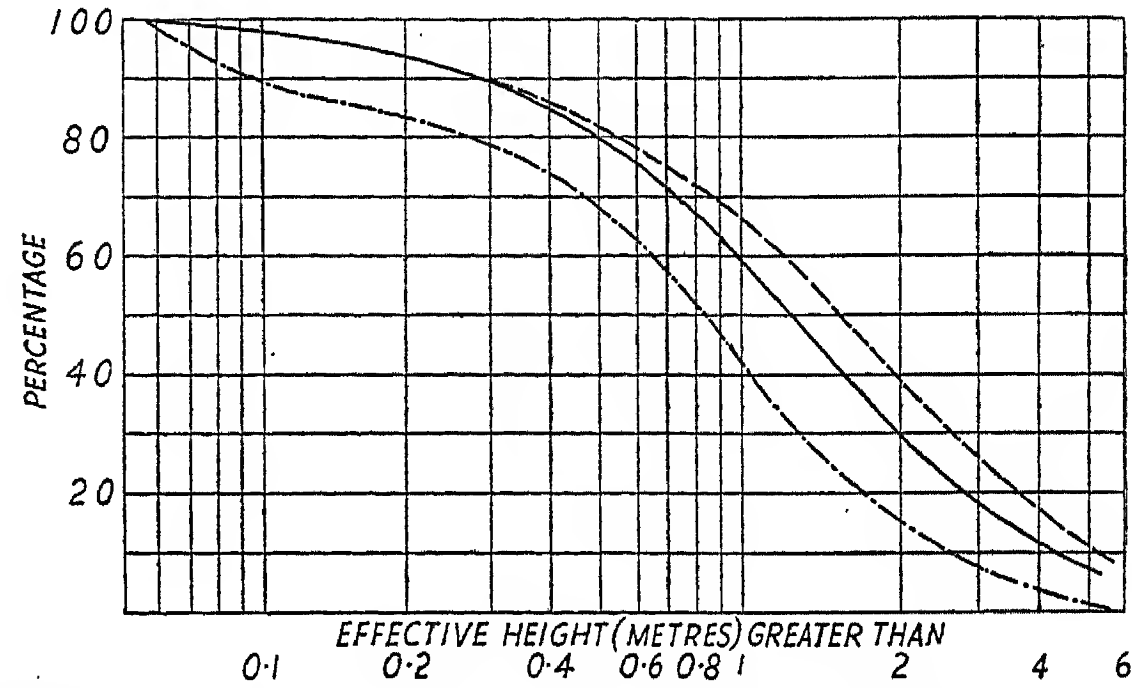

Fig. 23.—Frequency curves of the effective heights of aerials on various wavelengths.

——————— 261 m.
— — — — — — 342 m.
—·—·—·—·— 1 500 m.

of the aerials of the listeners who had complained of interference disclosed that these curves did not differ appreciably from those of Fig. 23 for the total number of aerials. Separate curves were also made of the effective heights for indoor and outdoor aerials on the three frequencies. As a rough generalization, it can be stated that the effective heights of outdoor aerials were of the order of 3 times the effective heights of indoor aerials.

The coupling between the mains and the aerial, expressed as attenuation for symmetrical and asymmetrical conditions, is given in Figs. 24 and 25. It is interesting to note that no relationship was apparent between effective height and coupling.

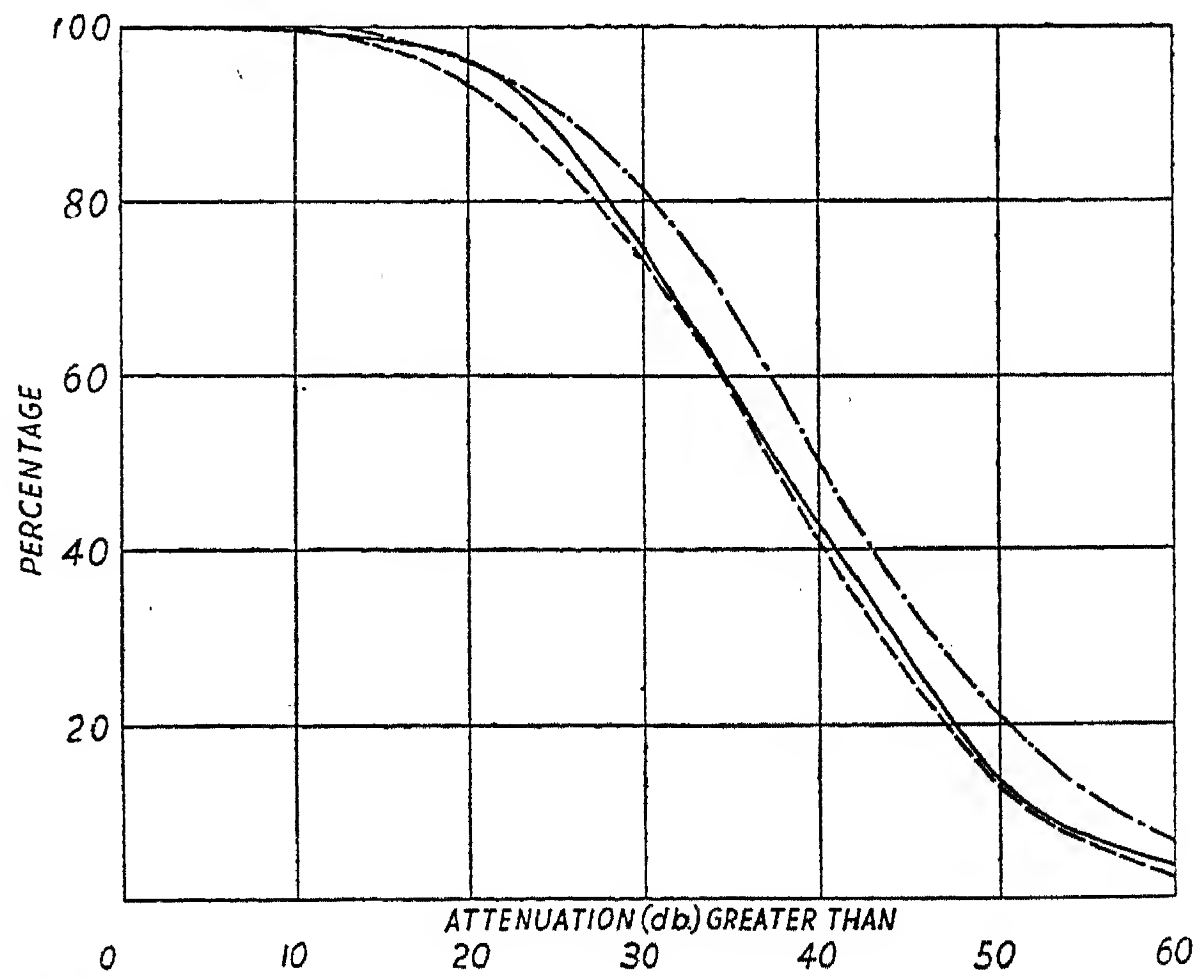

Fig. 24.—Transmission characteristics of domestic mains on various wavelengths for the symmetrical condition.

——————— 250 m.
— — — — — — 450 m.
—·—·—·—·— 1 600 m.

Interference can be propagated along the supply mains either as a difference of potential between the two conductors themselves or as a difference of potential between

the mean potential of the conductors and earth. As previously mentioned, the former path is generally referred to as the symmetrical path and the latter as the asymmetrical path. Owing to mutual cancellation of effects the radiation due to currents flowing in the symmetrical path is generally much less than the radiation from currents flowing in the asymmetrical path. The impe-

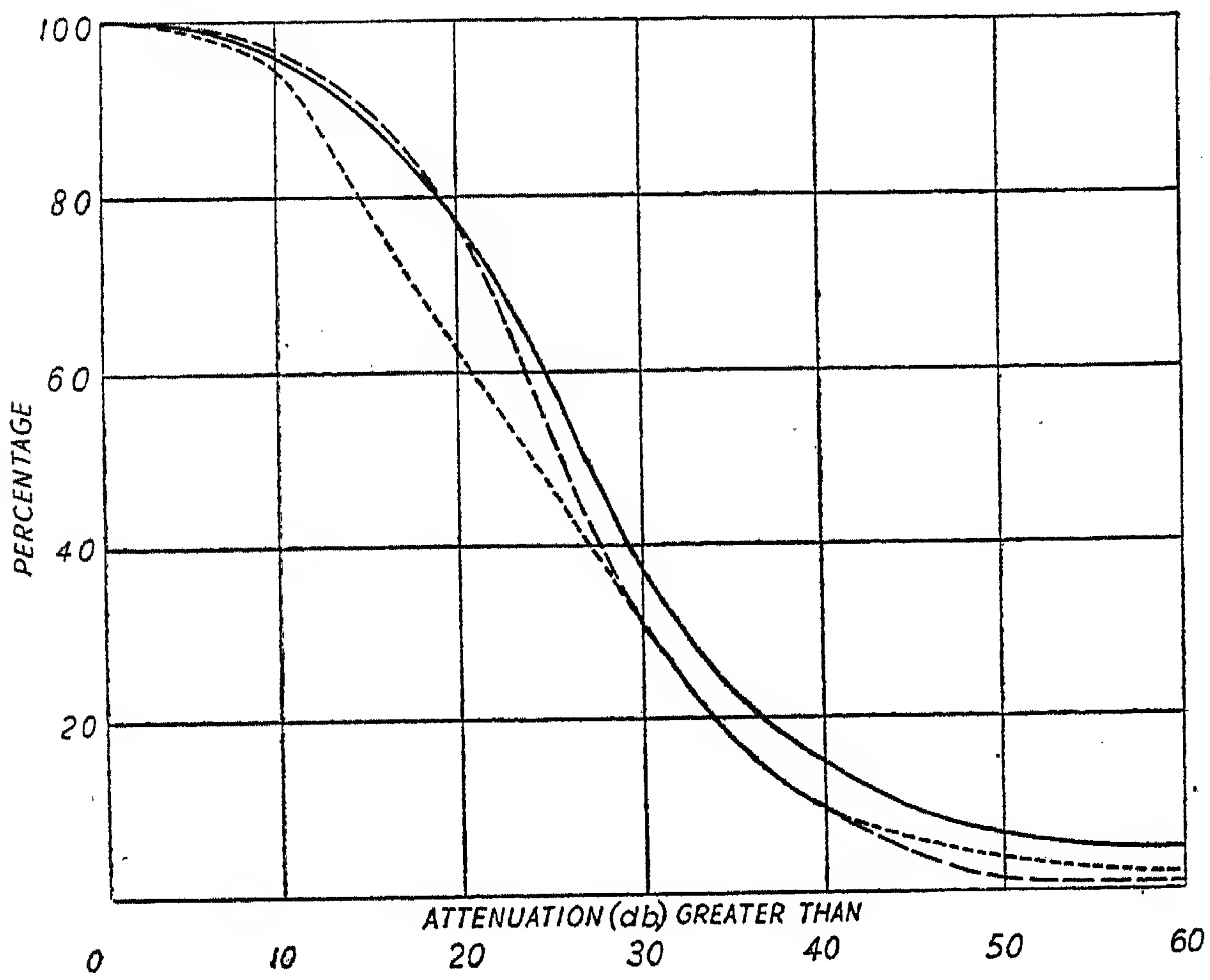

Fig. 25.—Transmission characteristics of domestic mains on various wavelengths for the asymmetrical condition.

———————— 250 m.
— — — — — 450 m.
- - - - - - - - - 1 600 m.

dance of the mains was measured for both the symmetrical and the asymmetrical condition by applying a sinusoidal h.f. voltage through a calibrated variable capacitance to the unknown impedance. The impedance could then be determined from a knowledge of the variable capacitance, the frequency and voltage of the oscillator, and the voltages across the variable capacitance and across the unknown impedance.

The measurement of the interference from machines necessitates the use of a mains network to ensure that the appropriate voltage is selected for measurement and that other noises propagated along the mains are not included in the measurement. A suitable form of mains impedance network, shown in Fig. 26, provides for the impedance of the mains to be balanced with respect to earth. For measurement of the symmetrical component the measuring instrument is applied across the resistance network of 200 ohms shunted by 600 ohms, while for measurement of the asymmetrical component the 200-ohm resistance is short-circuited and the two 300-ohm branches connected in parallel between the mains and earth. Thus in each case the interference path is terminated by a resistance of 150 ohms. Recently it has been provisionally agreed to measure the asymmetrical component between the mid-point of the 200-ohm resistor and earth, avoiding the short-circuit between the mains terminals. The test results are usually the same with either method. The two chokes prevent any interference voltage present from the mains being introduced into the measuring set. In the U.S.A. a value of 600 ohms has been adopted for the equivalent mains impedance.

The impedance of the supply main was found to vary over wide limits. In general it can be said that the impedance will be between 30 and 300 ohms for the symmetrical condition and between 100 and 1 000 ohms for the asymmetrical condition, for frequencies of 700 to 1 200 kc., and from 15 to 150 ohms and from 30 to 200 ohms respectively for the two conditions at a frequency of 200 kc. The value of 150 ohms is arbitrary, but a standard is essential since the interfering voltage varies to some extent proportionately to the mains impedance.

With regard to the noise voltage from interfering items measurements have been made, at the time of writing, on 352 electrical appliances of various kinds, as follows:—

(a) *Domestic appliances* (*up to* 500 *watts*)	No.
Bells	6
Dusters (hand)	2
Fans	34
Floor polishers	5
Heating pads	1
Lamps	2
Mixer (juice extractor)	3
Gramophone motor	2
Refrigerators	17
Sewing machines	8
Vacuum cleaners	43
Violet-ray apparatus	4
Washing machines	3
Water heater	3

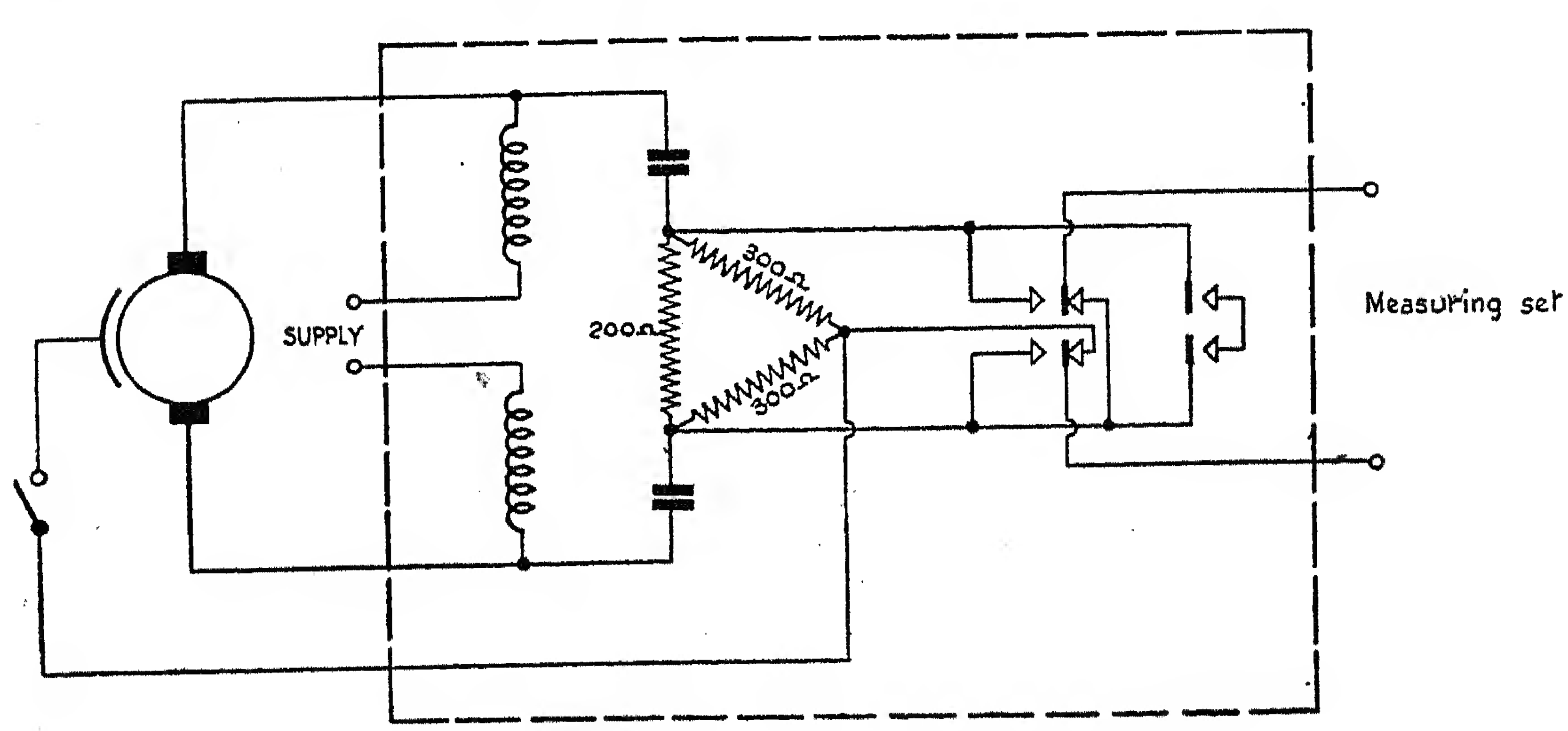

Fig. 26.—Artificial mains impedance network.

(b) Non-domestic appliances (up to 500 watts)

	No.
Adding machines	3
Coffee grinders	2
Dental apparatus	12
Diathermy apparatus	2
Flashing signs	4
Furnace (electric)	1
Hair clippers	6
Hair cutters	1
Hair dryers	20
Meters (clock, etc.)	2
Motors	38
Neon signs	6
Rectifiers	1
Rotary convertors	4
Thermostats	3
Tools (portable electric)	85
Traffic signals	2
Turntable (motor display)	2
Valve rectifiers	2
Vibrators	6

(c) All types of machines, 500 W–3 kW

	No.
Dust-precipitation plant	1
Furnaces (electrical)	2
Motors	6
Ovens	3
Starting panel	1
Welders	4

The magnitude of the unsuppressed interference from these appliances was as shown in Table 7.

Table 7

Category	Level of unsuppressed interference* (db. above 1 μV)							
	Maximum				Mean			
	At 190 kc.		At 1 000 kc.		At 190 kc.		At 1 000 kc.	
	S	A	S	A	S	A	S	A
Category A (up to 500 W)								
(i) Domestic appliances, frame earthed	100	103	92	95	70	63	67	61
(ii) Non-domestic, frame unearthed	124	90	96	81·5	72	50	70	50
(iii) Non-domestic, frame earthed	124	116	102	97	77	76	66	68
Category B (500 W to 10 kW)	122	115	121	116	88	82	81	75

* S = symmetrical, A = asymmetrical.

(ii) Electric lifts.

The interference from the sources, already enumerated in Section (2) (*a*) (iv), which may be comprised in a lift installation, appears also as interfering voltages at the supply terminals, which, as regards origin, type, and frequency spectrum, are similar to the interference fields already described. Table 8 shows figures obtained with some representative types of installation. When a mercury-arc rectifier or rotary convertor is used for local supply, the mains noise of the installation is that appropriate to such items, which are considered separately elsewhere.

The h.f. impedance of a lift installation is indeterminate for noise of the click type. For motor noise the values correspond to those for large motors. Tests on Lift (ii) (Table 8) gave 60 and 130 ohms (inductive) on the long and medium wave-bands respectively.

(iii) Neon signs, traffic lights, etc.

The interference from neon signs may be either directly radiated or mains-borne. In these signs the current flows only during a short period of each cycle, as the ignition voltages and extinction voltages are high. In consequence the current wave is very peaky and considerable interference is generated. Some of the larger types of sign cover an extensive area and produce appreciable radiation. The disturbance caused by the radiated field is usually less than that due to mains-borne interference, and it is possible to adopt a remedy which is effective in both cases. Single-contact signs and multiple-contact signs produce interference of which the major portion is usually mains-borne. The interference from traffic lights is wholly mains-borne, as the metallic screening of all equipment in these appliances prevents radiation. The spectrum of interference from such plant is, as might be anticipated, similar to the general spectrum from spark discharge such as is shown in Fig. 9 referring to interference from overhead lines. As might be expected, the intensity tends to increase as the frequency of measurement is decreased, up to and beyond the limits of broadcast reception.

(iv) Converting and generating plant

The interference on the supply side due to motor-generators is that appropriate to large motors, which is normally small, although minor defects in commutation may cause abnormal interference. The same applies largely to the output side and to large rotary convertors and balancers, the interference from which is generally

of the order of 1 or 2 millivolts except in abnormal instances.

Mercury-arc rectifiers form a recent development which has received special consideration, since they are frequently installed for local use during change-over from d.c. to a.c. supply as well as for distribution and traction. Normally either one pole is earthed or the rectifier feeds the outers of a 3-wire system, the neutral wire being earthed and supplied from a balancer. It is then found that a condenser connected between lines reduces the interfering voltage between either line and earth, and accordingly it is desirable to measure the asymmetric voltage between each pole and earth separately. Similarly, the impedance of the system supplied exercises an important influence. Measurements are therefore made either with the rectifier connected as in actual use, or with an h.f. impedance of 150 ohms, or the open-circuit h.f. voltage is measured. The latter is the highest voltage which normally occurs, and, if the internal impedance is known, the voltage across a known load may be computed. Fig. 27(*a*) shows the relation between the "maximum" voltage, the open-circuit voltage, and the short-circuit current, for one of the rectifiers tested. The "maximum" voltage is that obtained when the h.f. load resonates with the rectifier.

The interference is continuously distributed over the broadcast bands. With the steel-tank type, the h.f. voltage is usually only of importance in the long wave band, since the voltage decreases rapidly between 150 and 300 kc., being fairly constant for higher frequencies

Table 8

INTERFERENCE VOLTAGES AT MAINS TERMINALS OF LIFTS

Type of lift	Level of loudest interference (db. above 1 μV) across 150 ohms			
	Symmetrical		Asymmetrical	
	900 kc.	180 kc.	900 kc.	180 kc.
(i) Hand controller, d.c. operation (driving motor at bottom of shaft)	90	90	90 98 (+) 88 (−)	58 58 62
(ii) Similar to (i), but driving motor at top of shaft	92	98	80	64
(iii) Similar to (ii)	88*	87†	94*	96†
(iv) Push-button type, d.c. operation (driving motor at top of shaft)	77*	84†	81*	85†
(v) Similar to (iv)	82	84	81	86
(vi) Push-button type, a.c./d.c. operation, motor-generator supply	40–50	42–56	40–50	42–56

* G.P.O. tests at 1 000 k.c. † G.P.O. tests at 190 kc.
Plus sign (+) indicates positive main to earth, minus sign (−) indicates negative main to earth.

Table 9

EFFECT OF GRID CONTROL ON INTERFERENCE FROM MERCURY-ARC RECTIFIERS

Degree of grid control*	0·1	0·5	0·7	0·8	0·9	1·0	Rectifier
Asymmetrical voltage (db. above 1 μV) at 200 kc.				51	50	37	Glass bulbs, 2/200 kW
	115	115	112	107	101	92	Glass bulbs, 20 kW
		92	92	92			Steel tank, 500 kW
Asymmetrical voltage (db. above 1 μV) at 1 000 kc.				45	40	15	Glass bulb, 100 kW
	100	97	94	92	90	87	Glass bulb, 20 kW
		75	71	72			Steel tank, 500 kW

* Ratio of output voltage with grid control to output voltage without grid control.

[Fig. 27(*b*)]. The glass-bulb type may show an increase of interference with frequency at lower frequencies, but when it is connected to a load of low h.f. impedance, e.g. a cable distribution network, the higher frequencies are attenuated and the interference tends to follow a variation similar to that for steel-tank rectifiers. In such circumstances, the h.f. voltage across the feeders due to a non-grid rectifier does not exceed about 10 mV in the long wave band and about 1 mV in the medium wave band. Provided the rectifier is stable the magnitude of the load supplied has only a minor effect. The use of grid-control, however, causes an increase in interference as the degree of control is increased. Most of the increase occurs as the grid-control ratio varies from 1 to 0·8 (see Table 9); a higher degree of grid control does not give much further increase in interference.*

The h.f. impedance of a glass-bulb rectifier is usually greater than 100 ohms and may be 400 ohms, whereas the impedance of the steel-tank type rarely exceeds 50 ohms. Accordingly, the reduction in interference due to a load of low h.f. impedance is greater in the former than in the latter case. This refers mainly to cable distribution networks where the h.f. impedance may be about 10 ohms. Where a small rectifier gives a local

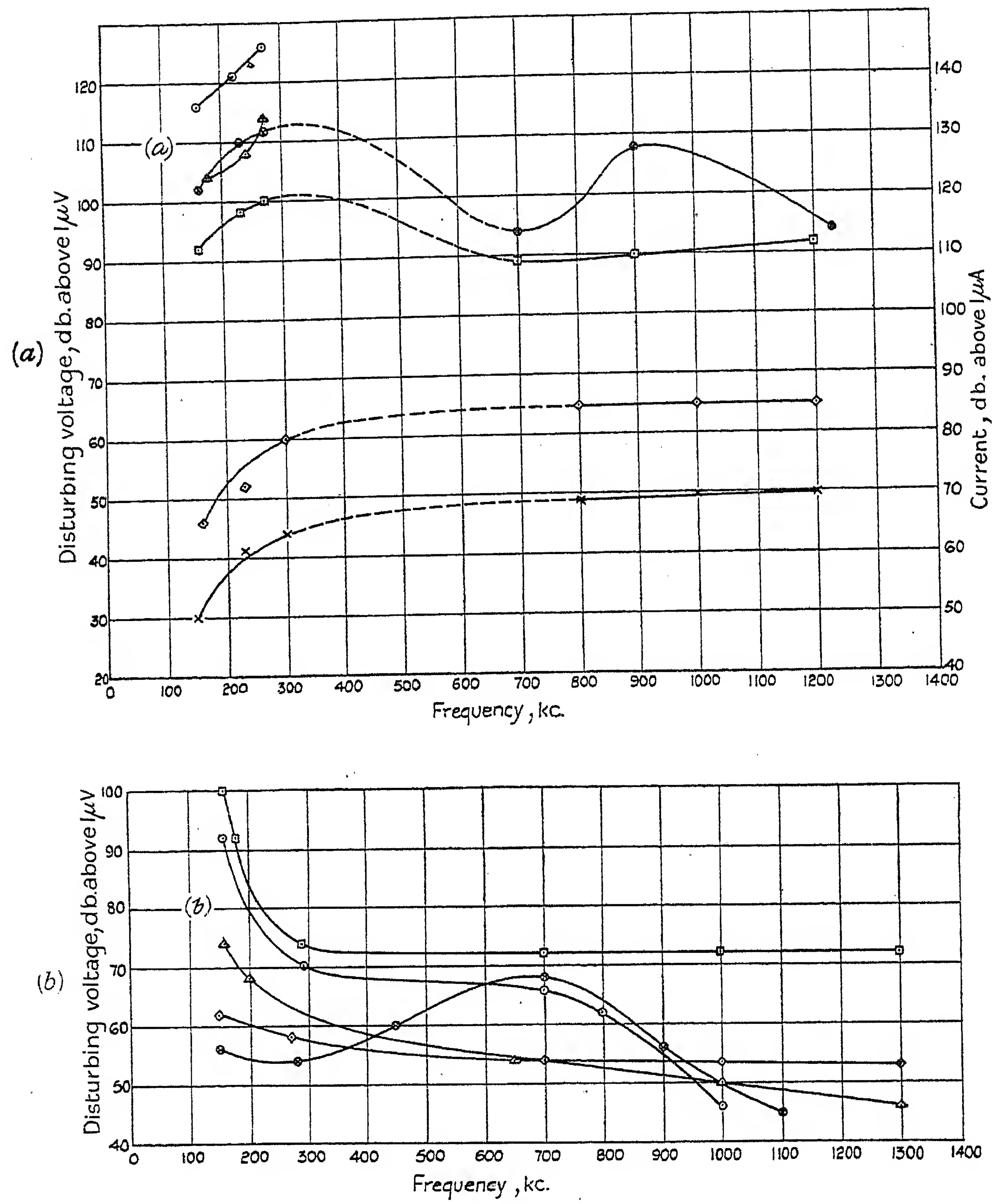

Fig. 27.—Interference from mercury-arc rectifiers.

(*a*) Maximum and open-circuit voltages and short-circuit current, for glass-bulb grid-controlled 6-phase 20-kW rectifier.

- ⊕ — ⊗ — Open-circuit voltage, grid-control ratio 0·7.
- ⊡ — ⊡ — Open-circuit voltage, grid-control ratio 0·97.
- ⊙ — ⊙ — Balanced voltage, grid-control ratio 0·7.
- △ — △ — Open-circuit voltage, grid-control ratio 0·97.
- ◇ — ◇ — Short-circuit current, grid-control ratio 0·7.

(*b*) Variation of interference with frequency.

- ◇ — ◇ — Asymmetrical (lines bonded), system load impedance, 4 glass bulbs (800 kW), grid-control ratio 0·89.
- ⊗ — ⊗ — Asymmetrical (lines bonded), load impedance 150 Ω, 2/3 phase, glass-bulb 5-kW rectifier without grid control.
- ⊙ — ⊙ — Positive line to earth, 150 Ω impedance, 300-kW steel-tank rectifier without grid control.
- ⊡ — ⊡ — Asymmetrical (lines bonded), load impedance 150 Ω, 500-kW steel-tank rectifier, grid-control ratio 0·73.
- △ — △ — Asymmetrical (lines bonded), load impedance 150 Ω, 4 glass bulbs (270 kW), without grid control.

* The audio-frequency disturbance, i.e. the telephone harmonic factor, varies in a similar manner.

supply, the load impedance may be taken as of the order of 150 ohms, as for domestic items, and so the reduction in interference is not great.

Small rectifiers may be supplied from the domestic a.c. mains, and then the interference on the a.c. side must be considered. It is usually much less (one-tenth to one-third) than on the d.c. side, and appears largely independent of the conditions on the d.c. side.

(3) METHODS OF SUPPRESSION

At the present time there is in this country no legislation protecting the licensed listener against radio interference, and a member of the general public who finds his reception interfered with or possibly spoilt has no redress apart, possibly, from applying in the High Court for an injunction for abatement of nuisance. The Postmaster-General, so far as his own commercial services are concerned, is in a somewhat better position, as he receives protection under the Telegraph and other Acts against interference with his services by power lines. As the commercial receiving stations are normally located well away from industrial or residential areas, many of the ordinary sources of interference are rarely troublesome and new overhead power lines are one of the few likely sources of interference.

In a number of other European countries legislation has been enacted with the object of protecting the broadcast listener from excessive and unnecessary interference with reception. This state of affairs is of considerable importance to British manufacturers of electrical appliances as, unless their goods are adequately suppressed as regards electrical interference, they may be refused entry into foreign countries. Moreover, foreign interference-free goods from countries with legislation may enter the British market and compete successfully with the unsuppressed goods of the British manufacturers. The question naturally arises whether it is essential, for the prevention of interference, to apply the remedy to the source of interference, or whether it is possible to modify the wireless receiver and aerial in such a manner that the interference is not received.

It is undoubtedly possible in many cases of interference to effect considerable relief by taking adequate measures at the receiving point. There remains, however, the larger proportion of cases where the interference is actually present as an electromagnetic wave of a frequency identical with that of the desired signal and for which no modification at the receiver can produce alleviation.

The Post Office has during recent years provided a free service to broadcast listeners for the purpose of dealing with cases of interference with broadcast reception. Where it is possible by modifications to the receiver or to the aerial system to avoid the interference, the listener is given advice accordingly. Where, however, no alleviation can be obtained in this way the source of interference is traced and, with the permission of the person owning the plant, the simplest and most economical method of suppressing the interference is ascertained. The owner is then persuaded, if possible, to adopt the remedy. It says a good deal for the public-spiritedness of electrical-plant owners in general that in the vast majority of cases very little persuasion is necessary to induce them to adopt suitable remedies.

A vast amount of work and annoyance would be saved, however, if some scheme of suppressing at least the smaller items of electrical plant at the manufacturers' works were adopted. The bulk suppression of interference in equipment, involves, however, a number of important considerations and requires some degree of international agreement, as otherwise plant which is suppressed sufficiently to meet the requirements of one country will not meet the requirements of some other country. It would be a great advance, therefore, if international agreement could be obtained as to a value admissible for the interfering noise voltage of an electrical machine or appliance when measured at the factory.

This value of admissible noise will depend on: (i) The h.f. field of the transmission to be protected. (ii) The degree of modulation of the transmission. (iii) The tolerable l.f. signal/noise ratio. (iv) The effective height of the listener's aerial. (v) The coupling between the receiving aerial and the interfering item. In regard to (i) and (ii), it is obvious that in the presence of a strong well-modulated signal from the desired transmission a given level of interference will produce far less annoyance than in the presence of a weak or poorly modulated signal. The transmission of music requires a wide range of modulation depths, which cannot, in general, be increased.

In connection with the work of the C.I.S.P.R. it has been agreed to consider the average field to be protected as being of the value of 1 mV per metre modulated at 80 %. Regarding the tolerable l.f. signal/noise ratio, it has already been mentioned in Section 1 (*a*) that as the result of tests by the C.I.S.P.R. the limiting value of this ratio has been found to be 40 db. when referred to the level of wanted signal at maximum modulation.

The fixing of an admissible value of noise is essentially a matter of compromise, as the choice of a very low figure would involve high cost in suppression services, whereas the adoption of too high a figure would relieve the cost of suppression at the expense of providing a higher signal field from the broadcasting service. In the latter connection there is a definite limit to the power of broadcasting stations, imposed by international agreement. The B.S.I. has agreed that, for frequencies between 200 and 1 500 kc., the maximum permissible interfering voltage at the mains terminals of a machine shall be 500 μV and that the interfering field strength shall not exceed 100 μV per metre at a distance of 10 yd. For example, if in a given case the effective height of aerial was 1 m. and the mains attenuation was 37 db., a field of 1 mV per metre would be adequately protected from mains-borne radiation.

(a) Suppression at the Source

The general principles of interference suppression are now generally realized, and in the case of the majority of smaller electrical appliances can be covered by general rules and specifications. The larger and more complicated electrical equipments, however, will generally require individual investigation and treatment for satisfactory suppression.

In suppressing interference at the source one of two

courses may be pursued: either to prevent the generation of the interference, or, alternatively, if it is impossible to prevent the generation of the interference, to limit its effect by preventing its radiation or passage to the power supply mains. The first course can often be adopted in the case of interference from switching operations by preventing the sudden growth and sudden decay of current in the circuits in question. Circuits of the type used for spark-quenching are suitable for this purpose.

The majority of cases, however, do not lend themselves readily to this treatment, and it becomes necessary to prevent the interference leaving the source. This is done by screening or modifications of the unscreened portions of the circuit as far as radiation is concerned, and by the use of filter circuits to prevent the passage of the interference to the supply mains.

(i) Low-power items.

The methods to be adopted for the suppression of low-power equipment have been disclosed in earlier papers,* and the results of work and experience to date are embodied to a large extent in B.S.S. No. 613—1935.

A large percentage of cases can be cured by the use of condensers alone; for example, the items of equipment referred to in Table 7 were all suppressed down

Table 10

Category	Percentage	No. of machines tested
A (*a*)	64	90
A (*b*)	73	34
A (*c*)	27	168
B	65	17

to a level of 200 μV of interference (46 db. relative to 1 μV), and this was accomplished by the use of condensers only in the percentages of cases given in Table 10. The use of condensers alone across the terminals of the appliance will be more efficacious where the internal impedance of the appliance to h.f. currents is high. The arrangement can be assumed to be equivalent to a potentiometer consisting of the machine impedance and condenser impedance shunted across the source of interfering voltage. The impedance of the condenser is low, so that the greater proportion of potential-drop occurs across the machine impedance and a very small proportion occurs across the condenser and supply mains. Care must of course be taken that the value of condenser chosen is such as not to resonate with the machine impedance at any frequency liable to cause interference, as in this event the interference may be accentuated. Furthermore, it is essential that the condensers with their associated connecting leads have as little inductance as possible, as otherwise their efficiency will be greatly reduced at the higher frequencies.

The I.E.E. Wiring Regulations recommend that all exposed metal on machines, when such metal is less than 8 ft. above the floor, shall be earthed. The Regulations also deprecate the use of 2-pin reversible plugs and recommend that for portable appliances the framework should either be of non-metallic material or protected with insulating material. As these Regulations are not always obeyed it is necessary to safeguard the users of such appliances from the possibility of electric shock.

When condenser suppressors are fitted to portable machines one condenser is usually necessary between the supply mains and one condenser between the neutral and the frame. With the use of 2-pin plugs it cannot be guaranteed that the latter condenser will remain connected as originally fitted, and it has therefore to be limited to a low value in order to avoid the risk of shock. This limitation has the effect of reducing the efficacy of the suppressors, but it has been found that if two $0{\cdot}005$-μF condensers are fitted in series across 250-volt a.c. supply mains and the centre point of the condensers connected to the framework, then a reasonable degree of suppression can be obtained for a large number of machines, and it has been shown by extensive tests that in the event of the user touching the framework and earth simultaneously no appreciable shock can be felt.

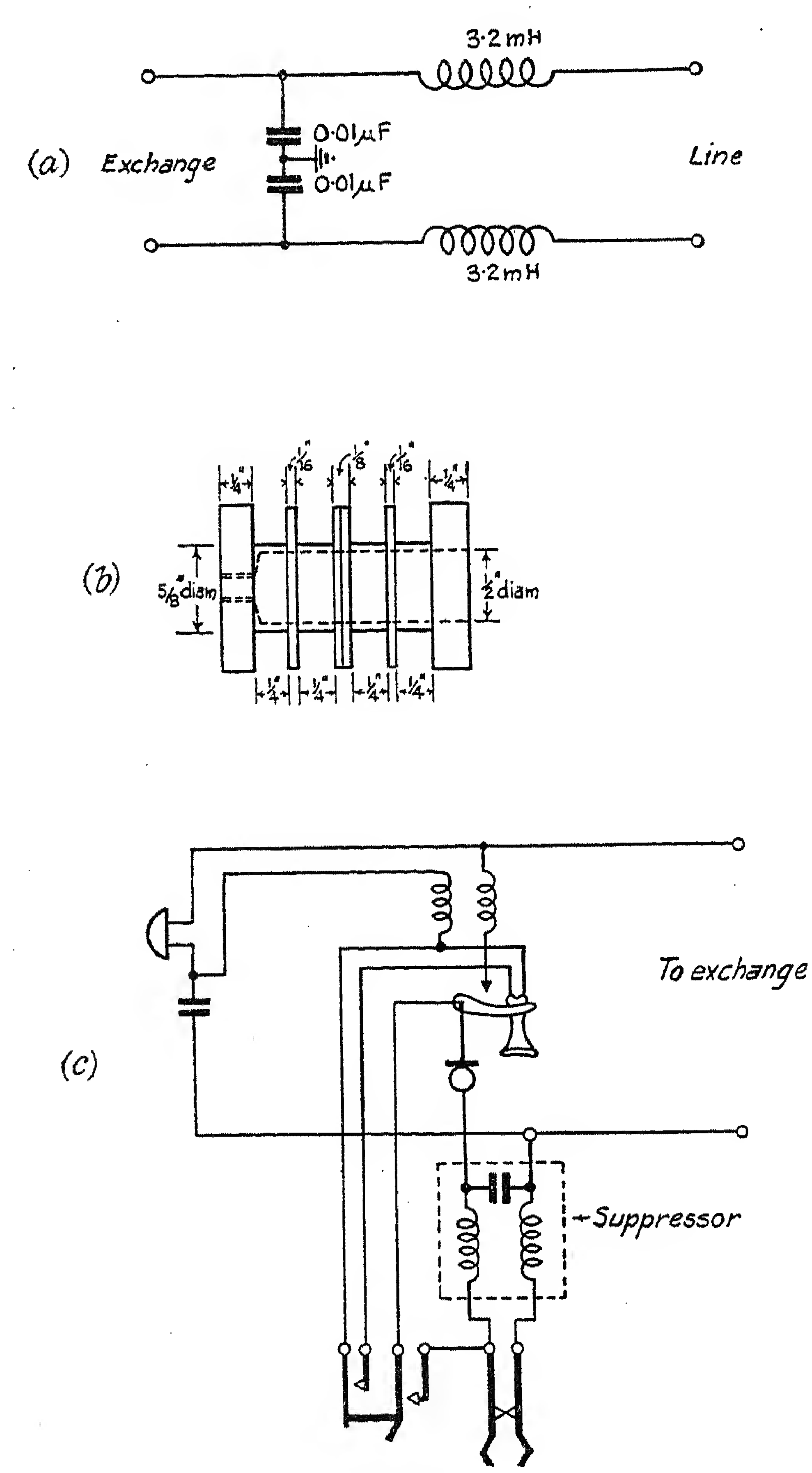

Fig. 28

(*a*) Line suppressor for automatic telephone exchange.
(*b*) Coil spool (moulded bakelite).
(*c*) Dial suppressor at subscriber's premises.

* For example, A. MORRIS: *Journal I.E.E.*, 1934, vol. 74, p. 245.

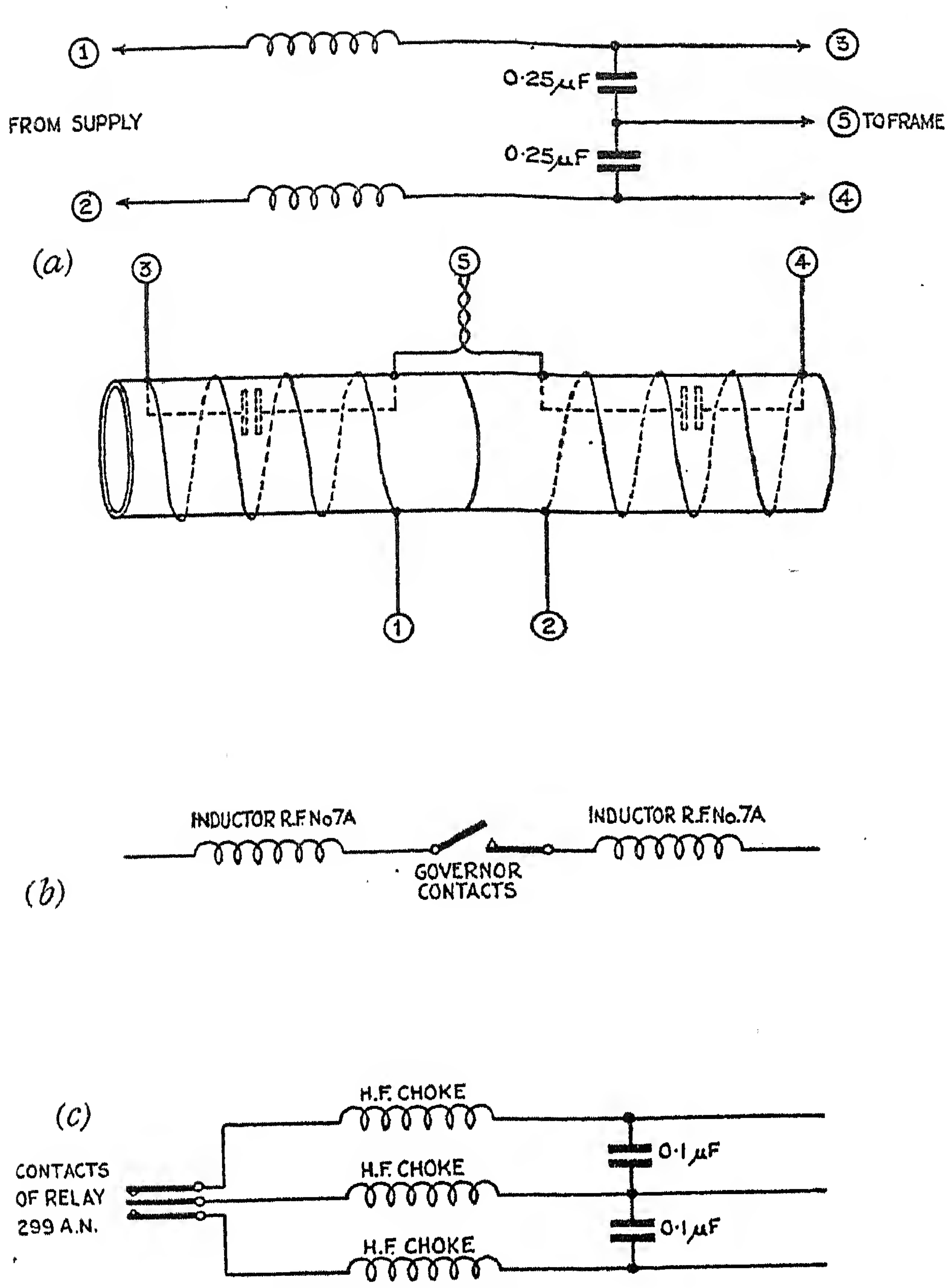

Fig. 29.—Interference suppressors for P.O. teleprinters.

(a) Mains input filter.
(b) Governor suppressor.
(c) Relay suppressor (for duplex voice-frequency circuit).

This method has been adopted as standard practice by the Post Office.

In the case of telecommunication apparatus it has already been mentioned that, as far as automatic telephone plant is concerned, the most effective method of suppressing interference from an exchange with overhead distribution is to provide filters on every circuit leaving the exchange building. Details of the line suppressors used for the purpose are given in Fig. 28(*a*). The impedance of the coils increased from about 3 500 ohms at 150 kc. to a peak of over 250 000 ohms at 1 400 kc., after which it decreased to about 100 000 ohms at 1 500 kc. The self-capacitance of each coil was about 5 $\mu\mu$F. Details of the coils used are given in Fig. 28(*b*). The suppressors are mounted in units for 50 lines and for 20 lines, and the overall dimensions of a 50-line unit are 1 ft. 7 in. high × 1 ft. 10 in. wide × 10 in. overall depth. The 20-line unit is similar, with an overall width of 1 ft. $3\frac{1}{2}$ in. Particulars of the suppression achieved by this equipment are given in Table 6.

The interference sometimes experienced from dialling impulses can be alleviated by fitting a suppressor at the subscriber's dial. A typical arrangement of a suppressor for this purpose is shown in Fig. 28(*c*). The condenser is of 0·1 μF and is of the non-inductive tubular type. Coils of various types have been used, wound over the condenser. One arrangement consists of two coils of No. 36 S.W.G., d.s.c., having a loop inductance of 25 μH and a loop resistance of 0·88 ohm.

With regard to interference from machine telegraphs, this rarely causes trouble except in commercial receiving stations. One remedy in such cases is to install the machine telegraph apparatus in a screened enclosure

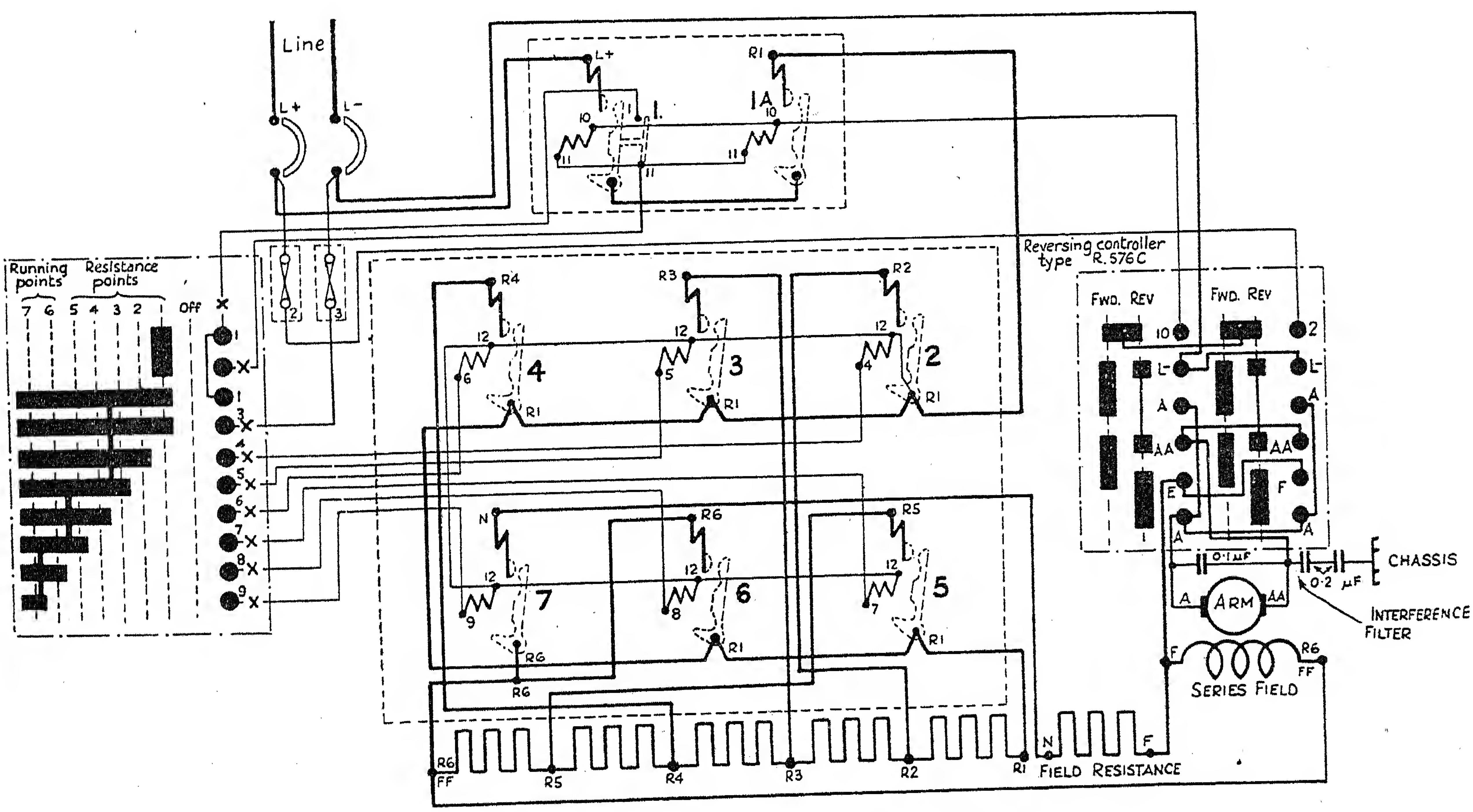

Fig. 30.—Schematic diagram of typical trolley-bus electrical equipment.

with filters in all incoming conductors. Another remedy is to provide suppression filters on the machine telegraph equipment. In severe cases it may be necessary to employ both remedies.

In the case of Post Office teleprinters installed at a radio receiving station, it was found necessary to fit suppressors to the mains supply, to the governor contacts, and to the sending and receiving relay. Details of the filters used are given in Fig. 29. The mains filter consists of two coils, each of 54 turns of No. 24 S.W.G. d.c.c. copper wire, pile-wound in six groups of nine turns on two tubular $0 \cdot 25$-μF non-inductive condensers. They can be fitted in the base of the teleprinter. The governor filter consists of two coils. A greater degree of suppression is obtained by screening these coils before fitting them within the base of the teleprinter. For the relay suppressor, commercial short-wave h.f. chokes are suitable as the current to be carried is small. This equipment was found to give suppression for the motor and governor interference over the band 150–19 000 kc.; less complete suppression might be sufficient in cases where the received signals are of the order of 100 μV per metre or more.

(ii) Trolley-buses.

The three main methods of suppression of the interference from trolley-buses are by treatment of individual items, suppressors on the overhead wires, and chokes in the main supply leads from the trolley arms.

In the first method, inductors are connected in each controller lead and condensers and resistors are connected across the controller contacts; there are also condenser filters on the driving motor, and on the brake compressor or exhauster motor, and inductors in the supply to the lighting motor-generator, if present. The details of the suppressors for one type of trolley-bus are shown in Fig. 30. The capacitance connected to the chassis does not exceed $0 \cdot 1$ μF, and it is considered that the shock obtainable from the discharge of this condenser would, under the worst condition, be inappreciable. Normally the leakage to earth from the chassis is adequate to prevent the potential of the latter from differing from that of the ground in the vicinity, but it is occasionally possible for the chassis to become effectively insulated from earth. By means of these filters, the interference from the items to which they are connected can be reduced to field strengths of the order of 20 db. above 1 μV per metre in the medium wave band, and 40 db. above 1 μV per metre in the long wave band, measured at a distance of 10 yd. from the vehicle and under the trolley wires. Individual suppression ratios as high as 80 db. have been reported in some tests. Table 11 shows some representative test-results for the suppression of interference due to controller operation.

Table 11

Frequency (kc.)	Type of vehicle	Nature of filters	Degree of suppression (db.)	At
300 and 1 100	Rheostatic braking	4-mH chokes	26	Town A
1 000 / 200	Company B	10-mH chokes on each side of each contact	53 / 30	Town B
900 / 200	Regenerative braking	ditto	43 / 33	Town C
900 / 200	Company C	ditto	54 / 21	Town D
900 / 200	Regenerative-rheostatic braking	ditto	28–42 / 29–33	Town E
900 / 200	ditto	ditto	36 / 36	Town F
900 / 200	Regenerative braking	5-mH chokes ditto	46 / 11	
900 / 200	ditto	As above, but with $0 \cdot 1$ μF across contacts	>72 / 54	
900 / 200	Regenerative-rheostatic braking	10-mH chokes on each side of each contact	40 / 30	Depot H
900 / 200		As above, but with resistances across certain contacts	80 / 60	Depot H
900 / 200	Mechanical braking only	10-mH chokes on each side of each contact	24 / 29	Town G
900 / 200	Air brake only	ditto	27 / 30	Town H
900 / 200	ditto Company D	ditto	43 / 42	Town J
900 / 200	ditto Company E	ditto	43 / 42	Town J
900 / 200	Eddy-current braking, Company F	ditto	42 / 40	Town J

In actual operation, interference due to collectors and due to the main contactors also occurs. The latter is usually small, as has already been noted, while the former is now much reduced by changes in design and maintenance. Accordingly the method will give adequate suppression both for radiation from the system and for direct radiation from the trolley-bus, except when the collector noise is unduly high, or when there are other sources of interference coupled to the overhead system, or in some of the exceptional conditions of weather, etc., already mentioned in Section (2).

If the lines themselves are loaded with condensers, the interfering currents pass to earth at adjacent condensers, while the impedance of the line is reduced, thus decreasing the voltage corresponding to a given interfering current. The first effect increases to some extent in both wave bands for an interval of 350 yd. In some instances, adequate suppression can be obtained by condensers alone, as indicated in Table 12.

Suppression by condensers alone may not always be adequate in severe instances, but condensers may conveniently be used in conjunction with other methods since they eliminate collector noise and line noise from other sources, and the failure of a unit does not invalidate the suppression since the influence of the remaining units is exercised over the whole of the line. In this way the frequency of severe "clicks" may be considerably reduced, to the point at which they become tolerable, while systems or sections which are the source of strong interference may be isolated from the systems and sections serving residential areas where the streets are narrow.

If choke coils are connected in the main supply leads

Table 12

SUPPRESSION OF TROLLEY-BUS INTERFERENCE BY LINE CONDENSERS ALONE AND IN CONJUNCTION WITH OTHER SUPPRESSORS

Trolley-bus suppression apparatus	Site	Distance of test position from overhead line (yd.)	Interference level (db. above 1 μV per metre)	Condenser spacing (yd.)	Suppression (db.)	Frequency (kc.)	Remarks
Unsuppressed	A	10	47	440	20	1 000	Single trolley-bus, normal operation
Unsuppressed	A	10	42	80	25	1 000	Single trolley-bus, normal operation
Double-hump chokes ..	A	10	43	440	27	1 000	Single trolley-bus, normal operation
Unsuppressed			44	80		1 000	Single trolley-bus
Single-hump chokes ..	B	5	47	80		1 000	Normal service
Single-hump chokes ..	B	5	29	80		1 000	Single trolley-bus
Unsuppressed	A	10	32	240	30	200	Single trolley-bus
Unsuppressed	A	10	19	80	43	200	
Single-hump chokes ..	A		32	240			Normal service
Double-hump chokes ..	A	10	34	440	28	200	Single trolley-bus
Single-hump chokes ..	B	5	44	80		200	Normal service
Unsuppressed	B		34	80			Single trolley-bus
Single-hump chokes ..	B	5	33	80			Single trolley-bus

with the normal impedance of the line, which, however, can only vary within narrow limits unless special conductors are used, so that the effect will depend mainly on the resistance of the earth connection of the condensers. The second effect depends also on the internal impedance of the vehicle being greater than the external impedance. The efficiency of condensers thus varies according to the earth resistance of the standards to which the condensers are usually earthed and, to some extent, according to the vehicles in question. Tests on systems where the earth resistance was of the order of 10–20 ohms, as measured by ordinary earth-testers, indicated suppression ratios up to 40–50 db. in the long wave band and 20–30 db. in the medium wave band, with condensers of $0{\cdot}5\ \mu$F connected to earth on each wire at 80-yd. intervals, the degree of suppression decreasing with increase of interval, and being about 20 db. to the trolley-bus equipment, the interfering voltages generated therein are prevented from reaching the line while currents due to collector disturbances are prevented from circulating in the system. These chokes must carry a heavy current, however, so that their design forms a difficulty on account of the non-paying load and the reduction in maximum tilting-angle which may be caused. The latter objection may be minimized by winding the coils with aluminium strip in lieu of copper. They are usually mounted on the roof, but may be mounted in the cab without very much loss in efficiency. Existing designs are mainly of two types, the single-hump type, giving a maximum impedance in one wave band, and the double-hump type, having an auxiliary circuit (Fig. 31) such as to produce two maxima of impedance, one in each wave band. Suppressions of 20–30 db. have been obtained by these means, but dis-

placement of the maxima from the test frequency and severe collector noise may considerably reduce the suppression.

The present conclusion is that for severe cases, where the streets are narrow, a combination of suppressors on each disturbing item on the trolley-bus, with a few line condensers at special situations such as turning circles, crossings, and section points, is desirable. If the line is in bad condition or if wheel collectors are used, more line condensers may be necessary. In other cases the line condensers may be omitted, or line condensers may often be employed alone, if at sufficiently frequent intervals. For wide streets where aerials can be located at, say, 50 yd. from the route, main choke coils may be used. Where these are already in use the suppression they give may, if inadequate, be suitably reinforced by the addition of line condensers.

(iii) Electric lifts.

The component items and circuits of electric lifts are treated separately in this paper, and the methods applicable have, in many instances, already been described; such as, for example, the main motor, the motor-generator, convertor, or rectifier in a.c. and a.c./d.c. systems; the gate-closing motors, bells, indicator lights, fans, and similar auxiliary equipment. The control circuits show some special features. If these circuits are operated from a panel in the car the interference must be prevented from flowing in the trailing cable and being radiated therefrom. To this end, chokes of about 6 mH should be connected in each lead, both at the panel in the car and at the controller where the relay coils are situated. In addition, condensers of 0·5 or 1 μF may be connected from each lead to earth on the trailing-cable side of the chokes. A less but often adequate degree of suppression can be obtained by mounting the chokes at the halfway box instead of in the car itself, while the filters at the controller panel or, at least, the chokes therein comprised, may often be omitted. In general, the more rigorous treatment is required in control circuits energized from the full mains voltage since these circuits are more highly inductive. In many modern lifts a.c. controls are used and need little suppression.

Control circuits, including gate interlocks, which do not enter the trailing cable are treated in a similar manner, filters being required at the operating switch and at the relay coil. If the wiring is in conduit or screened the chokes may often be omitted from the filters. Screened trailing cables have not yet come into general use.

The tripping, holding, and closing coils of the circuit-breakers and contactors should be furnished with condensers of 1 or 2 μF, connected between each end of the coil and earth. In some older types of lift these coils are directly controlled from the car, the circuit being included in the trailing cable. Severe interference is experienced in such circumstances, and the methods described previously for control circuits must be applied. It is also often advantageous to connect condensers up to 4 μF across the switch contacts in the car. The brake-magnet coil, which may also be a source of interference, can be suppressed to the extent of about 40 db. by means of an arc-suppressor of the rectifier type, as is often employed in inductive circuits. Such devices form an alternative in many instances to the condenser and choke-condenser filters described. The metalwork of the shaft should be well bonded to earth, since appreciable voltages may arise along the length of the shaft.

The interference passing into the supply mains, if the domestic supply or a system coupled thereto is employed, can be satisfactorily reduced by a mains filter of the normal choke-condenser type. Table 13 shows the methods and extent of suppression which have been achieved in some typical instances.

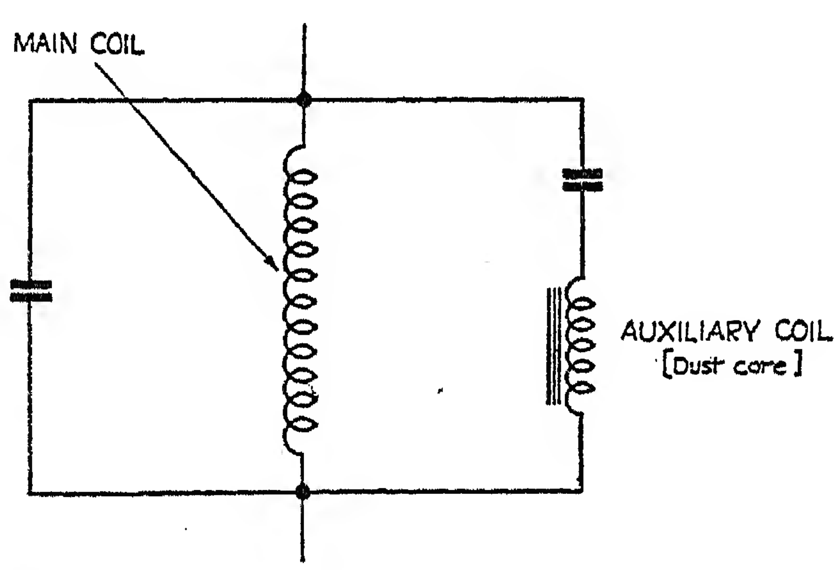

Fig. 31.—Schematic diagram of trolley-bus double-hump choke.

(iv) Ignition systems.

As regards the normal broadcast wavelengths, condenser suppressors of a conventional nature are applied to the various items of electrical equipment of automobiles, such as the dynamo, coil or magneto, wind-screen wiper, horn, etc. In addition, screened cable may be used for the wiring, the screen being bonded to the chassis. Such measures are mainly of importance for car radio where, in addition, or alternatively, the aerial and lead are screened if in proximity to the car wiring.

The spark system itself affects receivers along the route or in the neighbourhood, and requires special consideration. Complete screening is entirely effective but, at present, expensive and mainly employed in aircraft and for military and police purposes. The coil or magneto is encased in a low-resistance box to which is attached, by a metallic gland, the screened cable leading to the distributor, similarly encased in a metal box. The plug leads are also formed of screened cable, attached to the distributor and the plug by metallic glands completely enclosing the plug head and distributor terminals. The screened cable is bonded at intervals to the chassis.*

Automobiles may be partially screened by using screened and bonded ignition leads or by using a metal cover substantially enclosing the high-voltage circuit. It is then necessary to apply a choke-condenser filter at the battery terminals of the coil. This scheme appears sometimes to give adequate suppression both for car-radio and for external receivers. One serious disadvantage with screening is the capacitive load on coil or magneto, which may reduce its voltage unless it is specially designed, and decrease the life of the contact point.

* See Air Ministry Specification DTD GE 125, Issue 6, and B.S. Specification in course of issue.

Partial screening may in many cases meet this objection,* but difficulties will occur if existing coils are used with long-gap sparking plugs. It seems possible, however, that with these plugs certain other alleviating factors may play a part.

cylinder magneto or with a brush-type distributor, the resistors need only be mounted at the plugs. With magnetos, the distributor is usually incorporated in or close to the magneto so that no resistor is necessary in the distributor lead, but such a resistor is necessary

Table 13

DEGREE OF SUPPRESSION OF INTERFERENCE FROM ELECTRIC LIFTS

(a) Radiated

Type of lift (see Table 8)	Suppression condition	Level after suppression (db. above 1 μV per metre) at 10 ft. from C/L of lift	
		900 kc.	180 kc.
(i)	Chokes at panel	70	46
	Chokes at halfway box	62	47
	Chokes plus condensers (earthed) at panel	62	42
	Chokes plus condensers at car controller	48	40
	Do., plus chokes and condensers at panel	48	40
(iii)	Chokes at panel plus choke/condenser filter in mains	33	34
(v)	Chokes plus condensers (earthed) at halfway box	40	23
	Same filters at controller panel	36	21
(vi)	Chokes plus condensers (earthed) at panel (gate motor leads) plus chokes and condensers at motor switch contacts	16†	25‡

(b) Mains Interference

Type of lift (see Table 8)	Suppression conditions in supply leads	Level after suppression (db. above 1 μV)			
		Symmetrical		Asymmetrical	
		900 kc.	180 kc.	900 kc.	180 kc.
(i)	Chokes with condensers (earthed) on line side	52	62	45	46
(iii)	Chokes at panel plus choke/condenser filter in mains	39†	26‡	44†	28‡
(v)	Chokes with condensers (earthed) on line side	38	36	45	44
(vi)	None	45	48	45	48

† G.P.O. tests at 1 000 kc. ‡ G.P.O. tests at 190 kc.

On account of the difficulties mentioned, alternative methods have been studied which fall into two types—resistors, including resistor-condenser combinations, and choke-condenser units. Resistors must be placed as close as possible to the source of the spark, i.e. at the actual plug and distributor terminals. With a single-

when a long lead connects a coil to a distributor. The use of long distributed resistors as the plug leads themselves avoids duplication of resistors at each end and is more efficient for the same resistance value. In addition, the efficiency can be very considerably increased by covering a short length of the lead at the plug end by a screen of metal foil, as in Fig. 32, so as to form a small condenser of about 20 $\mu\mu$F, the foil being bonded

* With some car designs it is possible to enclose the whole of the ignition circuit in a single screen bolted to the engine.

to the cylinder block. This forms a network giving a high attenuation from the plug for very high frequencies. Table 14 indicates the degree of suppression which may be attained. The suppression necessary depends, with ultra-short waves, on the service field-strength envisaged

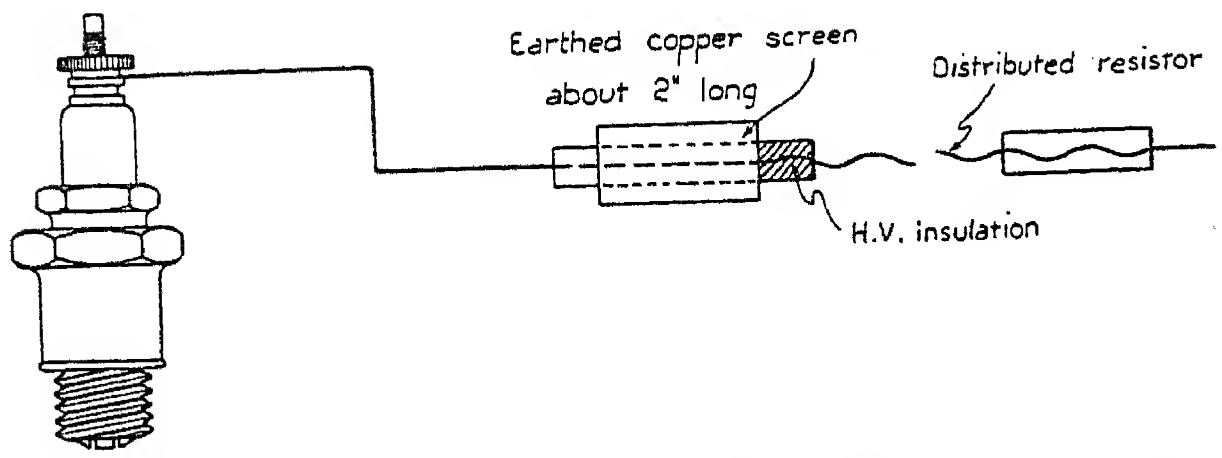

Fig. 32.—Distributed resistor, with screen, for ignition systems.

and the location of the receiver. In general, it appears from Section (2) that suppressions of not more than about 25 db. should prove satisfactory in the great majority of cases.

The figures in Table 14 were obtained partly on a model ignition system and partly from tests on a number of automobiles of various ages and sizes produced by the principal motor-car manufacturers. Often the degree of suppression required, after the ignition layout has been suitably arranged, is such that only a resistor in the distributor lead is necessary.

Table 14

Frequency (Mc.)	Resistance (10^3 ohms)	Suppression (db.)
Single-cylinder magneto		
12	100†	27
	50†	27
	25†	24
	25‡	34
45	25†	17
	25‡	23·5
	25*	16
Coil and 4-cylinder brush-type distributor		
21	25†	22
45	25†	25

Frequency (Mc.)	Resistance (10^3 ohms): Distributor lead	Resistance (10^3 ohms): Plug leads	Suppression (db.)
Coil and spark-type distributor			
12	20*	25†	29
	—	50†	30
45	20*	25†	20
	20*	30‡	40
	15*	10*	25
	5*	5*	15

* Carbon resistor.
† Distributed resistor.
‡ Distributed resistor with screen.

If h.f. chokes are employed at the plugs, it is essential to incorporate the small condenser, already mentioned, on the lead at its point of attachment to the choke, as is the case with the chief proprietary form of this suppressor. The suppressions thereby obtained by the use of suitable components have varied from about 18·5 db. at 50 Mc. to 30 db. at 12 Mc.

(v) Mercury-arc rectifiers.

With some exceptions, satisfactory suppression of the interference on the d.c. side is obtained by means of condensers connected between each output lead and earth or between the anodes and cathode and earth, or by a combination of these methods. By means of such condensers, of capacitance up to 1 or 2 μF, the disturbance can usually be reduced to 600 μV or less. Since a reduction of 10 db. may be allowed for attenuation in the cable to the nearest consumer, this corresponds to about 200 μV applied in a manner comparable to that associated with a domestic item.

With other types of system, with certain rectifiers of the grid-control type and with rectifiers not completely balanced or stabilized, a higher degree of suppression is desirable. This may be achieved by h.f. chokes inserted in each feeder, with condensers connected between the load side of each choke and earth. The inductance of these chokes is limited by the load current to be carried. Standard values for air-core chokes are 150 μH, 300 μH, 800 μH to 1 mH. The use of a choke with an iron core in shell form is of advantage as regards size and carrying capacity when dealing with heavy currents. Table 15 shows the methods of suppression adopted in a number of particular instances. A wide variation of efficiency of suppression is observed, and shows that regard must be paid to the type of load and relative impedances of load and rectifier in choosing the best methods of suppression. Item (2) in Table 15 is an example of this. The low suppression-ratios achieved with chokes in this instance are due to the fact that, owing to the low h.f. impedance of the system supplied, the insertion of chokes increased the interfering voltage at the terminals of the rectifier so as largely to neutralize the attenuation provided by the choke-condenser filter applied.

In conditions obtaining in this country a disturbance on the a.c. side needs treatment only in those cases where the domestic mains system is used and where the interference level of the rectifier is unusually high. Suppression can then be achieved by a filter of normal type with a choke in each phase and a condenser of 0·1 to 1 μF connected between the supply side of each choke and earth.

(vi) High-frequency medical appliances, and cases where screening is essential.

Although the suppression of the high-frequency interference arising from the operation of diathermy and similar types of apparatus is quite simple, the practical application may at times present some difficulty where apparatus is already permanently installed. It is therefore important that in all new hospitals and medical institutions provision should be made during construction for prevention of radiation by the means described later.

Two methods are available. The first is to redesign the apparatus in such a way that the secondary forms an output circuit which in linear dimensions is as small as possible, and which has a metallic return to reduce earth currents to a minimum. This method has so far not been adopted to any large extent, principally on the grounds of expense, but an experimental violet-ray set has been designed by the Post Office to these requirements and is practically non-interfering. The second method, which can be adopted for complete suppression, is the enclosure of the apparatus and patient in an earthed metallic screen and the provision of h.f. filters

Table 15

Suppression of Disturbance from Mercury-Arc Rectifiers

Type of rectifier	Capacity	Type of load	Condition of test	Suppression device	Frequency (kc.)	Suppressed level (db. above 1 μV)	Suppression ratio (db.)
(1) 6-phase, steel tank, non-grid	500 kW 460 V	Cable distribution system	Positive line to earth	2 μF each anode and cathode to earth, and on balancer	217	48	33
					900	39	26
(2) 6-phase, steel tank, non-grid	300 kW 480 V	Cable distribution system	Positive line to earth	12 μF each line to earth	150	52	— 1
					1 000	42	3·5
			Negative line to earth	12 μF each line to earth	180	49	8
					1 000	46	1
			Asymmetrical (lines bonded) to earth	1 μF each anode and cathode to earth, and between lines	180	55	9
					1 000	48	0
			Positive line to earth	150 μH in positive line, 12 μF to earth	180	49	2
					1 000	41·5	4
(3) 6-phase, steel tank, grid control	500 kW 480 V	Cable distribution system	Line to earth	0·1 μF each anode and cathode to earth, and between lines	180	82·5	12·5
					1 000	62·5	11·5
			Line to earth	200 μH in each line, 10 μF to earth on load side	180	47	25
					1 000	56	10·5
(4) Glass bulb, non-grid, two 3-phase units	480 V 10 A	Local supply	Line to earth	1 μF each anode and cathode to earth, and between lines	205	84	— 10
					900	64	6
			Line to earth	1 μF each line and neutral to earth	205	19	54
					900	30	40
(5) Glass bulb, non-grid (2 units, giving 12 phases)	270 kW 480 V	Cable distribution system	Line to earth	1 μF each line to earth	220	40·5	28·5
					1 000	36	11
				1 μF anodes and cathode, and between lines	220	27·5	40·5
					1 000	—	Order of 50
(6) 6-phase, glass bulb, grid control (0·89), 25 cycles per sec.	2 units gave 230 V, 200 kW	Cable distribution system	Line to earth	1 μF each line to earth	180	40	15
					1 000	49	6
(7) 6-phase, glass bulb, grid control (0·97), grid control (0·1)	360 V 60 A	Local supply	Line to earth	400-μH chokes in each line, 0·5 μF each line to earth	217	51	46
					900	58	32
				400-μH chokes in each line, 0·5 μF each line to earth	217	59	51
					900	58	42

Table 16

System	Cost per sq. ft.	Screening for walls, door, ceiling, and floor	Wire-mesh reinforced glass for window 3 ft. × 4ft.	Mains filter	Labour costs	Total cost
Metallized paper	½d.	£1 10s.	12s.	£4	£5	£11 2s.
Zinc-sprayed paper . .	2d.	£6 0s.	12s.	£4	£5	£16 12s.
Zinc-spraying on wall . .	1s., including labour	£31 10s. Floor covered with wire netting	12s.	£4	£1	£37 2s.
¼-in. galvanized netting . .	1d.	£3 10s.	12s.	£4	£5	£13 2s.

on all circuits entering the screened enclosure. It is also necessary that all water pipes, gas pipes, conduits, etc., be efficiently bonded to the screen.

Instances may occur in which the nearest broadcast listener, although situated outside the field of directly-radiated disturbance, is yet within the area over which receivers may be affected by the h.f. components propagated via the supply mains. Provided that the electric supply system in the locality is laid underground an adequate degree of suppression should be gained by the insertion of an h.f. filter at the point of entry of the supply mains to the premises in which the interfering apparatus is housed.

In the case of a violet-ray set used in a private house or in a hairdresser's establishment, a screening cubicle may be constructed very simply by stretching ¼-in. mesh galvanized-iron wire netting over a wooden frame and bonding this to similar netting laid on the floor. A cubicle having the dimensions 7 ft. × 6 ft. × 6 ft. 6 in. would be of suitable size and could be erected and draped to taste at moderate cost. In the case of a hospital or medical practitioner, however, it is usually more convenient to screen the room in which the electrical treatment is given. This may be effected by the use of any one or a combination of the following screening materials: metallized paper, zinc-sprayed paper, zinc spraying on the walls and ceiling, or small-mesh galvanized-iron wire netting. If the room to be screened is in course of construction it may be found practicable to employ wire mesh for screening purposes, as this can be embedded during the process of plastering, and when finished the screening would be hidden.

Metallized paper is initially very effective, but in one case its efficiency was found to decrease considerably with age, the resistance between adjoining strips of paper at pasted joints increasing as the paste dried out. It follows that if metallized or zinc-sprayed paper is used, special attention must be given to the permanency of the joints. Owing to the high cost of screening by spraying zinc directly on to the walls, this method has not been tried out in practice on an actual room. From tests carried out on small specimens, however, it would appear to be satisfactory.

As a guide to the relative costs of the various methods, the estimated costs of screening a room 12 ft. × 14 ft. × 8 ft. high are given in Table 16. The cost of a 15-ampere h.f. mains filter is also included in each case.

For decorative purposes, paint or wallpaper could be used to cover the screening in the case of the first three

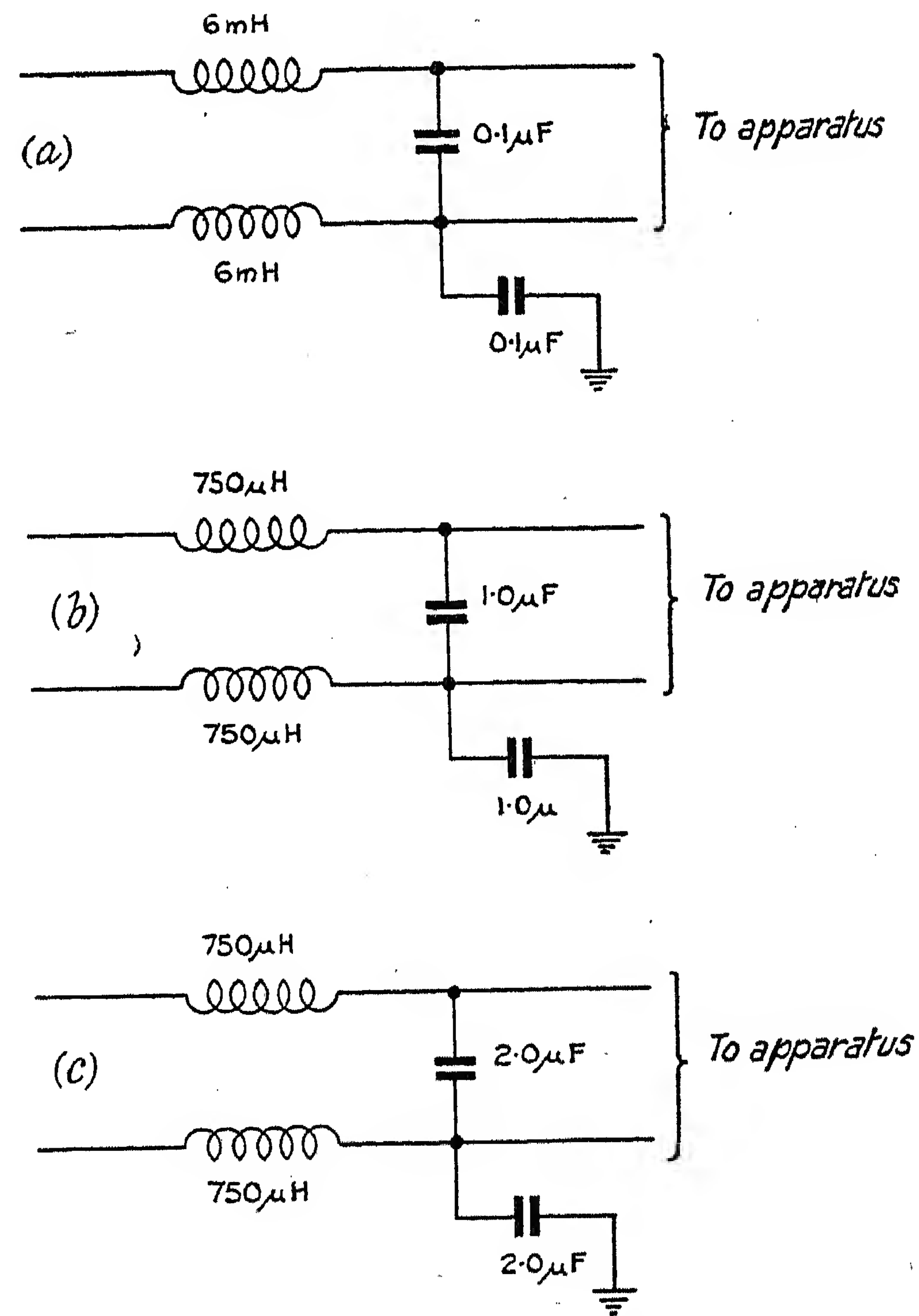

Fig. 33.—Suppressors used in tests on electromedical apparatus.

methods referred to in Table 16. The cost of this is not included. In the fourth method the wire netting can with advantage be embedded in the plaster of the walls and ceiling. If it is embedded during construction of a new building there is no additional cost. If re-plastering is necessary this will involve an additional cost of about £10. The metallized paper consists of

Table 17

PORTABLE HIGH-FREQUENCY MEDICAL SETS

Type of set	Frequency of measurement	Mains interference voltage measurement*: Suppressed (S) or unsuppressed (U)	Voltage values (db. above 1 μV): Symmetrical	Voltage values (db. above 1 μV): Asymmetrical	Suppressors, Type (Fig. 30)	Radiated field strength: Type of screen†	Values in db. above 1 μV per metre: 3 yd.	10 yd.	20 yd.	30 yd.
Portable violet-ray	kc. 190	U	74	102	(*a*)	None	81	40		
		S	39	37		C	42	5		
	800	U	85	87		None	74	38		
		S	36	38		C	34	2		
	1 200	U	87	88		None	59	36		
		S	40	38		C	17	0		
Portable violet-ray	190	U	68	74	(*a*)	None	79	49		
		S	31	33		C	33	0		
	800	U	65	70		None	60	37		
		S	34	34		C	26	0		
	1 200	U	78	86		None	53	31		
		S	38	42		C	20	6		
Spark diathermy, ultra-short wave, output 2·5 amp.	190	U	73	76	(*b*)	None		44	40	37
		S	33	37		C		18	16	12
						B		30	10	—
	800	U	72	78		None		50	45	39
		S	33	35		C		28	24	18
						B		35	26	—
	1 200	U	101	107		None		65	58	47
		S	34	42		C		40	36	24
						B		46	36	—
Spark diathermy, medium wave, output 2·8 amp.	190	U	89	89	(*c*)	None		50	42	24
		S	33	33		C		29	23	<20
						B		35	24	22
	800	U	82	88		None		56	50	34
		S	42	46		C		36	31	<20
						B		39	29	27
	1 200	U	77	84		None		59	52	45
			37	27		C		40	34	26
						B		42	32	28

* In the mains-voltage measurements the frames of the portable machines were not earthed, but the frames of the diathermy machines were earthed.
† Type of screen B: Galvanized-wire mesh applied to a room 16 ft. × 10 ft. × 8 ft.
Type of screen C: Paper-backed aluminium foil, metal 0·010 mm. thick, applied to a room 16 ft. × 10 ft. × 8 ft.

aluminium foil, 0·005 mm. thick, with a paper backing, and is applied in the same way as wallpaper with the foil outwards. There should be a "lap" of at least 1 in. at joints, and to ensure continuity a 2-in. strip of aluminium foil is pasted over the joints.

The interference from a number of types of portable electrotherapy or "violet-ray" apparatus and diathermy apparatus on the long-wave and medium-wave broadcast bands has been investigated. The levels of interference on the supply mains were measured with and without suppressors, and under the symmetrical and asymmetrical conditions. The radiated field-strength

was also measured at various distances under the screened and unscreened conditions. Typical measurements are given in Table 17. The types of h.f. filters used in the tests are shown in Fig. 33.

(b) Measures at Listener's Premises

(i) Type of aerial.

Wherever possible an outdoor aerial should be used, as this not only possesses a lower coupling with the supply mains but at the same time can have a much greater effective height than the indoor aerial. Frame aerials of the small type associated directly with the receiver are inefficient compared with the outside aerial, and although they possess certain directional properties these are rarely effective against interference because the frame aerial when rotatable on a vertical axis is directional only to vertically-polarized waves, and while the interference waves are largely vertically polarized there will be normally sufficient interference polarized in other directions to render the frame aerial of little avail. The most satisfactory arrangement will comprise an aerial well removed from the source of interference and connected to the receiver by some type of feeder system.

The feeder may be of the concentric or balanced 2-wire type. Where the feeder has to pass through an appreciable interference field as, for example, in going from top to bottom of a large building such as a block of flats, the single-core type of cable may not give such effective protection as a balanced type of cable, although much depends upon the actual circuits used in each case and the type of interference encountered. Enclosing a conductor in a metallic shield will not prevent its being affected by travelling waves of radiated energy; the shield will, however, protect the inner conductor from capacitive coupling to the electric supply mains, which is often a serious cause of interference. In the balanced transmission line both conductors are equally affected by radiated energy, but suitable terminal arrangements enable these effects to be balanced out. An arrangement of this kind is shown in Fig. 34(*a*). Here the aerial circuit includes the primary of the aerial transformer, the secondary of which feeds the balanced line. If the line is subject to radiated interference this will produce identical e.m.f.'s in each line conductor, which will set up currents between the mid-points of the line windings of the transformers and earth, but these currents will not introduce energy into the aerial or into the receiver.

A modification of the circuit shown in Fig. 34(*a*) is sometimes adopted, to allow the feeders to be used as the earth connection of the aerial itself. This arrangement is shown in Fig. 34(*b*), where the earth terminal of the primary of the aerial transformer is connected to the mid-point of the secondary. This circuit has the defect that any interference induced in the feeders in parallel enters the aerial through the primary of the aerial transformer, thereby producing loop currents which affect the receiver. This scheme, therefore, is not to be recommended in all cases, and it is preferable that the aerial, if possible, be earthed well away from the field of interference, as in (*a*). Where, however, the source of interference is capacitive coupling to the feeder the system will be effective if an earthed metallic screen is provided around the cable. Where the aerial can be placed so that the feeder can be buried or earthed along its route, the single-core concentric type will be suitable. Fig. 34(*c*) shows an arrangement of this kind.

One of the difficulties in connection with the provision of remote aerials and feeder systems arises from the increasing use of the so-called all-wave receivers which operate over a range of 150–30 000 kc. It is not easy to produce a feeder system which will operate satisfactorily over this wide range.

If the interference is most serious on the short waves

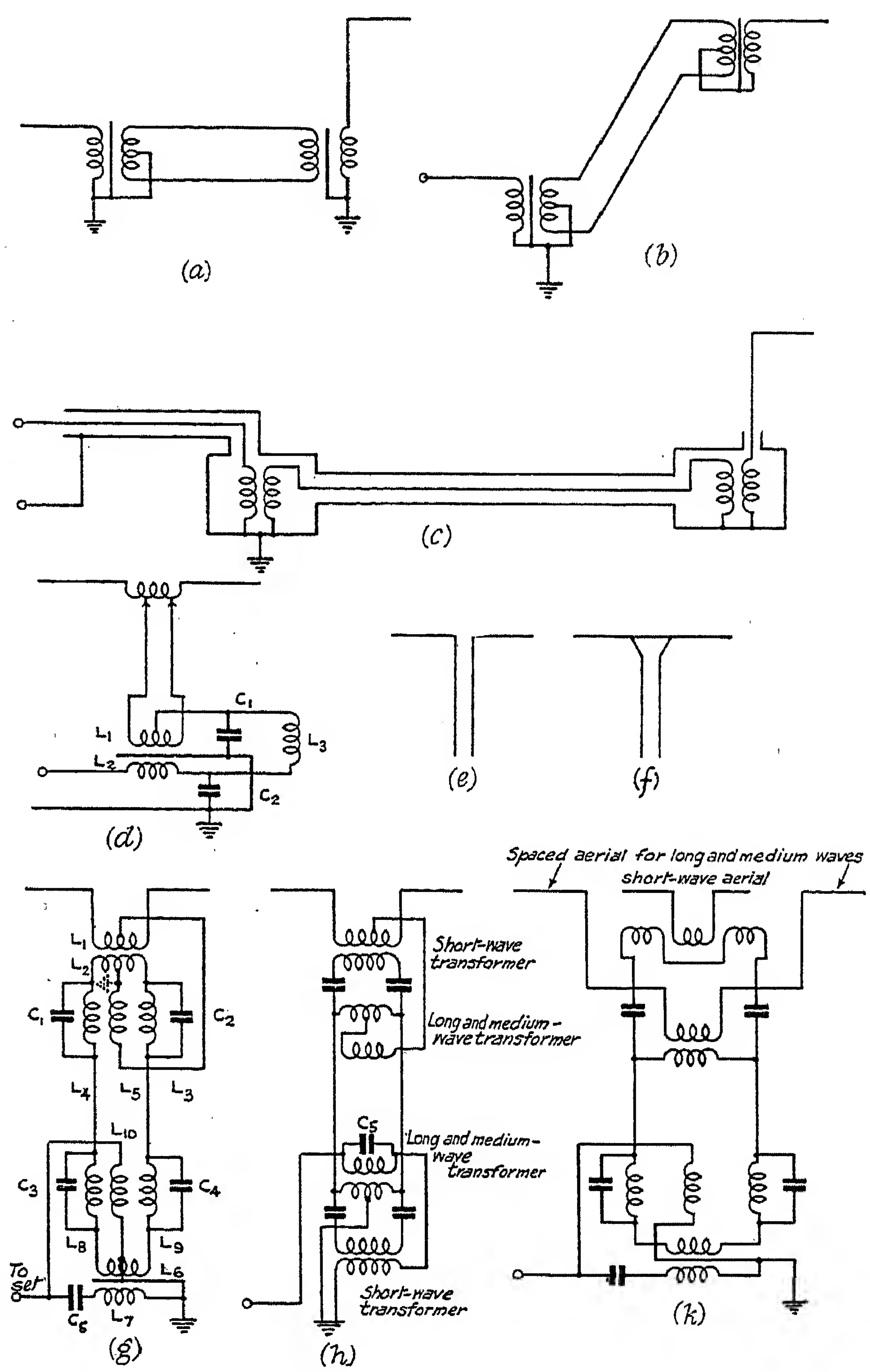

Fig. 34.—Aerial and feeder arrangements.

an arrangement can be adopted which works as a balanced system on short waves and as an unbalanced system on medium and long waves. An arrangement of this kind is shown in Fig. 34(*d*), where the aerial consists of a dipole with a coupling coil in the centre to which the feeders are tapped: L_1 and L_2 are respectively the primary and secondary windings of a short-wave transformer, C_1 and C_2 are condensers of values of the order of 50 $\mu\mu$F, while L_3 is an inductance of about 50 μH. At very high frequencies the aerial behaves as a dipole feeding the balanced line. At the receiver end of the line the loop currents set up a voltage across the secondary of the transformer, one end of which is connected to the

receiver while the other is effectively earthed through the condenser C_2. Short-wave interference induced in the line produces currents in the same direction in each of the feeders. These currents pass to earth through C_1. At these frequencies L_3 has a high impedance, so that very little of this interference passes to the set. At medium and low frequencies the dipole picks up very little energy as a balanced aerial, and a larger proportion of energy can be obtained from the dipole and feeder acting as a T aerial. This energy produces no output from the transformer, but as C_1 and C_2 have high impedances at medium and low frequencies the energy passes to the set through L_3, which has a comparatively low impedance. Alternative methods of connecting the dipole to the feeders are indicated in Figs. 34(*e*) and 34(*f*). This arrangement will not prevent the entry to the receiver of interference picked up by the antenna and feeder on medium and long waves.

Where an all-wave feeder system is of appreciable length it may be desirable to terminate it with transformers for long and medium waves as well as for short waves. An arrangement for this purpose is shown in Fig. 34(*g*). Here L_1 is the primary of the short-wave aerial transformer connected to a dipole aerial as shown in Fig. 34(*d*). The secondary winding is L_2, and both windings are centre-tapped. Across the centre taps is connected L_5, the primary of the long- and medium-wave transformer, having balanced secondaries L_3 and L_4 shunted by condensers C_1 and C_2 to allow passage for the short-wave line currents. The connections at the set transformer are somewhat similar. Here L_{10}, the secondary of the long- and medium-wave transformer, acts as a choke across the set on short waves, while C_5 presents a high impedance to long and medium waves. Other arrangements are possible; for example, the line windings of the transformers may be arranged in parallel instead of in series at one or at both ends of the line, while the secondaries of the set transformers may be connected in series instead of in parallel. One such possible arrangement is shown in Fig. 34(*h*).

The condensers C_1, C_2, C_3, and C_4 in Fig. 34(*g*), and C_5 in Fig. 34(*h*), can be arranged to be provided by the self-capacitances of the long- and medium-wave windings, but it is probably better that these windings have a low self-capacitance and the additional capacitance required be provided by small adjustable condensers. The condensers can then be adjusted to cover any capacitance unbalance in the windings.

None of these systems protect the feeders from radiated interference on long and medium waves, for the reasons previously mentioned. Such protection can be afforded by using a separate earth for the primary windings of the long- and medium-wave aerial transformer, as indicated in Fig. 34(*a*). The dotted connection, Fig. 34(*g*), indicates how this can be done. It is preferable to isolate completely the secondary circuits of the aerial transformers from the primary. The efficacy of the arrangement will of course depend on the removal of the earth connection from the field of interference.

If this cannot be arranged some form of balanced aerial for these wavelengths must be adopted. To be entirely effective, the aerial should consist of a loop or of two symmetrical spaced aerials, as, for example, in Fig. 34(*k*), which shows an all-wave balanced system having separate aerials for short and for medium and long waves. The disadvantage of such systems is that they are definitely directional when horizontal spacing is used, while if vertical spacing is used it is extremely difficult if not impossible to ensure that the system is balanced at all wavelengths.

In all systems it is necessary to provide a conductive path between the aerial and earth to prevent the accumulation of static charges on the aerial, and where the connection is not inherent in the circuit it can be provided by centre-tapping one or more of the transformer windings.

The primaries and secondaries of the transformers should be screened from one another, or other appropriate measures should be adopted in order that the balanced windings shall have equal capacitances to earth, and to avoid capacitance coupling between the primary and secondary windings. The transformer as a whole should preferably be screened, particularly in the case of the set transformer. Where interference is severe the receiver input lead should be screened also to within about an inch of the set, the screen being effectively earthed.

In the case of flats, where individual outdoor aerials are impossible, the best solution appears to lie in the provision of a single efficient aerial at the top of the building associated with a wide-band amplifier to the output of which a feeder is connected which is brought into every flat. The amplifier must be free from intermodulation effects, and provision must be made—by the insertion of a suitable impedance in the supply to each flat, or other means—to prevent as far as possible adjustments at the listener's receiver affecting other users of the service.

(ii) Type of receiver.

The increasing use of more sensitive receivers during the last few years has tended to accentuate the trouble due to interference, as the highly sensitive types now available render an efficient outdoor aerial unnecessary, with the result that there has been a tendency to use indoor aerials with their inherently higher coupling to the mains. At the same time the high sensitivity now available is a temptation to listeners to attempt reception of distant stations of low field-strength and subject to a higher degree of interference than the stronger local stations. The increase of interference perception due to the higher sensitivity has been offset to some extent by the improved selectivity of modern receivers, which, with their much narrower band of acceptance, reject much of the noise which would enter and affect the older and less selective type of receiver. In this connection, devices which allow the selectivity of the receiver to be increased when working on high gain are a valuable improvement. This improvement cannot be pressed beyond the limit where quality suffers.

The use of automatic gain control without a muting device for quenching the receiver in the absence of a carrier tends to give a false impression of interference, as the gain of the receiver rises to an excessive degree when it is being tuned between stations, with a corresponding increase in noise.

(iii) **Mains filters.**

The use of filters at the point of entry of supply mains to the listener's premises is a valuable aid towards the prevention of interference from plant outside the building connected to the mains, particularly in those cases where the level of interference or numbers of persons affected would not justify suppression at the source. Such filters normally consist of two condensers of capacitance $0\cdot5$–$2\cdot0\ \mu$F. One condenser is connected across the two supply mains, and the other condenser is connected from the neutral main to earth. Cases arise in which condensers alone suppress the interference to an inadequate degree; in such cases choke coils are used in addition. The condensers may be placed either on the street side of the chokes or vice versa, depending on the relative impedances of the street mains and the house mains. The best position can be found most easily by trial.

(c) Specifications and Procedure in Dealing with Interference

During the past few years a number of British Standard Specifications have dealt partially or wholly with radio interference. The first specification of the kind was B.S.S. No. 505—1933* [" Road Traffic Control (Electric) Light Signals "], which contained a clause requiring such equipment to be free from interference and an appendix dealing with electrical interference. B.S.S. No. 613—1935 (" Components for Radio-Interference Suppression Devices ") contains schedules specifying the recommended value of condensers, inductors, and resistors for different types of machines and appliances. B.S.S. No. 727—1937 (" The Characteristics and Performance of Apparatus for the Measurement of Radio Interference ") has already been referred to in Section (1). B.S.S. No. 800—1937 (" Standard Method for the Characteristics and Performance of Apparatus for the Measurement of Radio Interference ") defines the conditions for the issue of the Radio-Interference-Free mark.

Further specifications are in hand dealing with ignition systems, electromedical apparatus, trolley-buses and tramways, and radio receiving installations. B.S.S. No. 727 is in course of revision with a view to its extension to metre waves.

The procedure in Great Britain and Northern Ireland in dealing with interference is that all complaints, whether received by the B.B.C. or by the Post Office, are handed over to and investigated by the Post Office Engineering Department. Fig. 35 shows the number of complaints dealt with since 1929. The number of complaints dealt with in 1936 was 44 000, and the curve continues to rise. This increase in the number of complaints may be attributed to the increase in the number of listeners, the increase in the use of electrical appliances, and the growing knowledge of the public of the existence of the investigation service. In spite of the fact that the Post Office has given at exhibitions a certain amount of publicity to the work it is doing, it is believed that a very large number of listeners are still unaware of the service and are suffering in silence in conditions where it would be possible to provide relief. From information at the disposal of the Post Office it is believed that a considerable number of people, particularly those with houses in close proximity to electric railways, trolley-buses, and tramways, do not purchase licences or do not renew them because of their knowledge of the interference likely to be encountered; and that a large number of listeners tolerate more or less severe interference as they are aware that neighbours have complained or because they are too apathetic to register a complaint.

* Current edition is B.S.S. No. 505—1937.

In 1934 an analysis was made of 1 000 cases of interference, taken at random from all parts of the country,

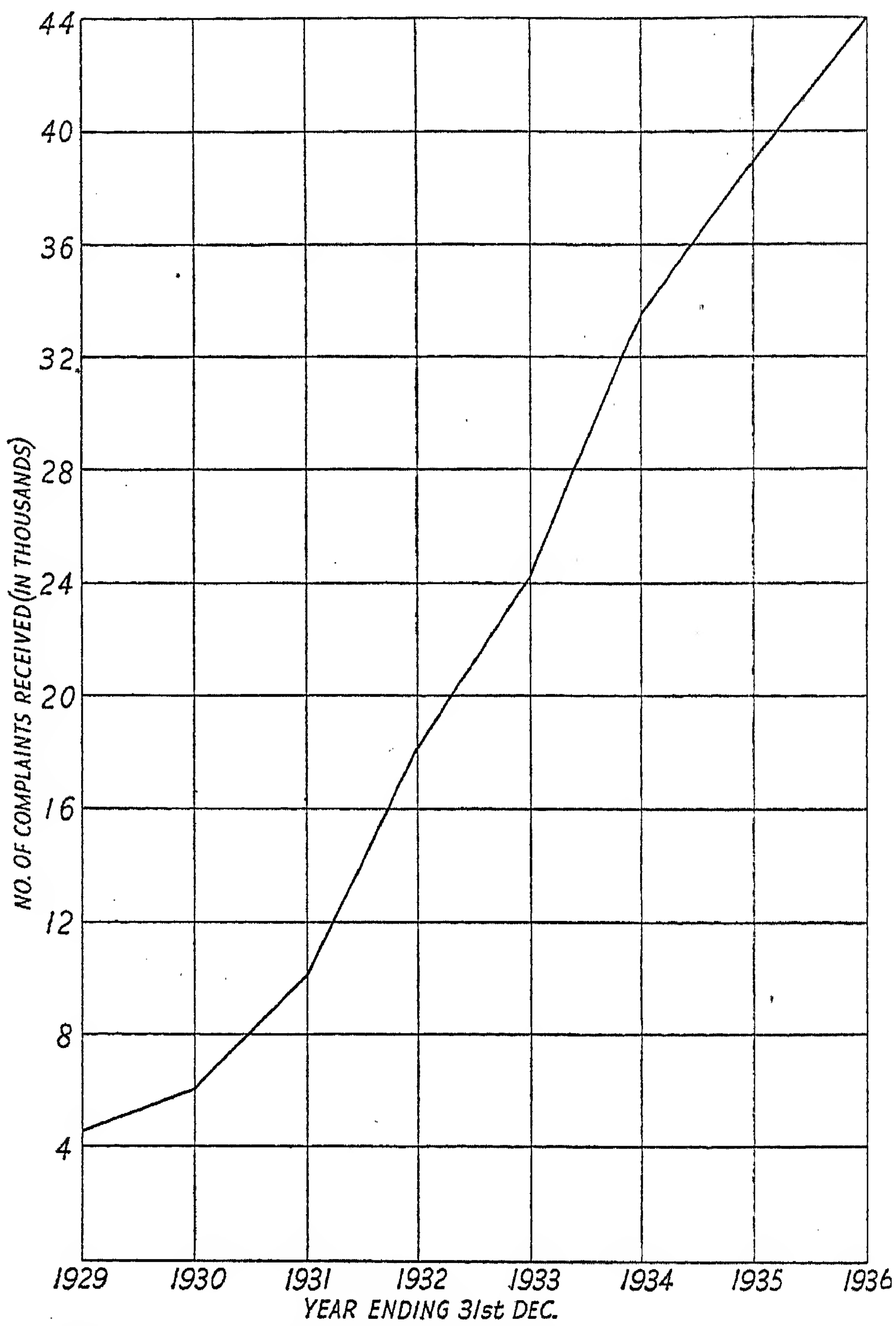

Fig. 35.—Interference complaints received by G.P.O.

in order to ascertain the distribution of interfering sources, with the following result:—

Type of plant	Percentage of total
Motors	50
Trams, trolley-buses, and electric railways	10
Flashing signs	5
Neon signs	4
Medical apparatus	4
Rotary rectifiers	3
Static rectifiers	3
Overhead power lines	2
Overhead telegraph and telephone lines	1
Underground power line	1
Railway signals	0·5
Traffic signals	0·5
Miscellaneous plant and apparatus	9
Faults at listeners' premises	7

The number of equivalent full-time Post Office staff employed in Great Britain and Northern Ireland on broadcast interference work is now of the order of 250. In order to improve their efficiency and widen their experience, special courses of instruction are held, by means of lectures and special demonstrations. The equipment available to this staff comprises 110 small motor vans, each supplied with an interference locator, portable wireless receiving set, screened leads, and a miscellaneous assortment of condenser filter units and inductors for experimental demonstration purposes. At the present time the investigations are carried out on the medium- and long-wave broadcast bands, but additional equipment is being provided to enable such work to be extended to the television band in the London area. The portable wireless receiving sets are of normal broadcast type, with self-contained batteries. Both h.f. amplification and the superheterodyne type are used. The sets are provided with internal frame aerials, and in addition have terminals for external aerial and earth connections. Jacks are also provided for headphone reception as an alternative to loud-speaker. The use of these sets enables tests to be made to verify that interference is actually present, and that the trouble is not due to faults on the complainant's apparatus. More recently a portable interference-locator has been developed by the Department, and it is the intention eventually to replace the majority of commercial types of portable receivers in use for interference work with this apparatus.

It is gratifying to record the co-operation which has been afforded by the parties involved. All branches of the electrical industry, the motor industry, the electro-medical trades, and the medical profession, have assisted in the preparation of and the necessary studies for the British Standard Specification relating to their equipment. The B.B.C., G.P.O., and Radio Manufacturers' Association have made special subventions to the E.R.A. in support of its work in this direction. Finally, in general, members of the public have willingly granted facilities and have followed the recommendations of the G.P.O. in specific cases investigated.

(4) ACKNOWLEDGMENTS

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BIBLIOGRAPHY

(a) General Principles and Policy

National Electric Light Association, Publication No. 25-633 (July, 1925).

A. LARSEN: *Elektroteknikeren*, 1928, vol. 24, p. 327; *Fjarde Nordiska Elektroteknikermotet-Foredrag*, 1929, p. 14; *Elektrotechnik und Maschinenbau*, 1931, vol. 49, p. 641.

M. D. HOOVEN: *Proceedings of the Institute of Radio Engineers*, 1929, vol. 17, p. 1390.

A. S. ANGWIN: Institution of Post Office Electrical Engineers, Professional Paper No. 137, 1932; *Telephone and Telegraph Journal*, 1933, vol. 19, p. 200.

H. O. MERRIMAN: Dominion of Canada, Department of Marine, Bulletin No. 2, 1932.

F. BROCK: Paris H.T. Conference, 1933, Paper No. 105.

A. MORRIS: *Wireless World*, 1933, vol. 33, p. 144; 1934, vol. 35, pp. 59, 445; *Journal I.E.E.*, 1934, vol. 74, p. 245.

E. AUBORT: Paris H.T. Conference, 1935, Paper No. 342.

Bureau of Standards Letter Circular No. 415, 1933.

E. MÜLLER: *Hochfrequenztechnik und Elektroakustik*, 1934, vol.44, p. 60.

"Broadcast Interference," *Electrician*, 1935, vol. 114, pp. 151, 179.

T. H. KINMAN: Publications of the B.T.H. Research Laboratories, 1935.

H. REPPISCH: *Telegraphen- und Fernsprech-Technik*, 1935, vol. 24, p. 95.

GULZGOFF: *Électricité*, Oct. 1935, p. 489.

A. DENNHARDT and E. H. HIMMLER: "Radio Interference Suppression" (J. Springer, Berlin), 1935.

J. H. REYNER: "Radio Interference and its Suppression" (Chapman and Hall, 1936).

J. NEALE: *Electrical Power Engineer*, 1935, vol. 17, p. 510.

A. C. WARREN: *Post Office Electrical Engineers' Journal*, 1935-36, vol. 28, p. 23.

(b) Standards, Regulations, etc.

Great Britain.

"Electrical Interference with Broadcasting" (Interim Report to I.E.E. Council), *Journal I.E.E.*, 1934, vol. 74, p. 801; (Final Report), *ibid.*, 1936, vol. 79 p. 206.

B.S.S. No. 505—1937.

B.S.S. No. 613—1935.

B.S.S. No. 800—1937.

B.S.S. No. 727—1937.

France.

Publications C-42 and No. 407 of the Union des Syndicats de l'Électricité.

M. ADAM: *Revue Générale de l'Électricité*, 1932, vol. 31, p. 678.

Journal Télégraphique, 1934, vol. 1, p. 143.

Germany.

E. EISER: *Elektrizitätswirtschaft*, 1931, vol. 30, p. 383.

V.D.E. Rules 0870/1933, 0873/1934, 0874/1934.

Elektrotechnische Zeitschrift, 1934, vol. 55, p. 1036.

Norway.

N. J. ANDERSON: *Elektroteknikeren*, 1931, vol. 27, p. 30.

Switzerland.

"Directions for Protection against Interference," *Bulletin, Association Suisse des Électriciens*, 1934, vol. 252, pp. 450, 635.

U.S.A.

National Electric Light Association Publications Nos. 32 and 33, 1933.

C.I.S.P.R.

Reports of Meetings (RI) 1, 2, 3, 4, 5, and 6, published by I.E.C.

(c) Methods of Measurement

Radio Engineering, 1931, vol. 11, p. 46.

J. W. ALEXANDER: *Hochfrequenztechnik und Elektroakustik*, 1932, vol. 40, p. 82.

W. WILD: *Elektrotechnische Zeitschrift*, 1933, vol. 54, pp. 149, 172.

C. R. BARHYDT: *General Electric Review*, 1933, vol. 36, p. 201.

F. EPPEN and K. MÜLLER: *Elektrische Nachrichten-Technik*, 1934, vol. 11, p. 257.

K. MÜLLER: *Veröffentlichungen aus dem Gebiet der Nachrichtentechnik*, 1934, p. 139.

K. MÜLLER and U. STEUDEL: *ibid.*, 1935, No. 2.

R. FELDKELLER: *ibid.*, 1934, p. 107.

W. E. STEIDLE: *ibid.*, 1934, p. 129.

E. AUBORT and W. GERBER: *Bulletin, Association Suisse des Électriciens*, 1934, vol. 25, p. 669.

M. DICK: *ibid.*, 1934, vol. 25, p. 715.

H. REPPISCH and F. SCHULZ: *Elektrische Nachrichten-Technik*, 1935, vol. 12, p. 124.

H. SUBRA: *Annales des Postes, Télégraphes, et Téléphones*, 1935, vol. 24, p. 368.

F. O. MCMILLAN and H. G. BARNETT: *Transactions of the American I.E.E.*, 1935, vol. 54, p. 857.

A. H. MUMFORD and P. L. BARKER: *Post Office Electrical Engineers' Journal*, 1935, vol. 28, p. 40.

F. R. W. STRAFFORD: *Wireless Engineer*, 1937, vol. 14, p. 242.

See also C.I.S.P.R. reports, already quoted in Section (*b*).

(d) Particular Sources of Interference

Domestic apparatus.

W. HASENBERG: *Elektrotechnische Zeitschrift*, 1930, vol. 51, p. 1523.

A. C. WIESE: *Elektrotechnik und Maschinenbau*, 1932, vol. 50, p. 384.

See also Sections (*a*), (*e*), and (*f*) of this Bibliography.

Traction systems.

F. EPPEN: *Elektrotechnische Zeitschrift*, 1924, vol. 45, p. 817; 1927, vol. 48, p. 97.

A. CLAUSING and P. MÜLLER: *ibid.*, 1928, vol. 49, p. 178.

H. KOPP: *Radio-Zeitung*, 1928, p. 803.

R. WICHMANN: *Elektrotechnische Zeitschrift*, 1929, vol. 50, p. 855.

R. BAUMEISTER and D. E. DOZIER: *A.E.G. Mitteilungen*, July 1934, p. 230.

H. HAERTEL and O. SCHNEIDER: *Siemens Zeitschrift*, 1934, vol. 14, p. 324.

E. W. SCHUMACHER: *Proceedings of the Institute of Radio Engineers*, 1935, vol. 23, p. 779.

J. E. CALVERLEY: *English Electric Journal*, 1936, vol. 8, p. 13.

Electrician, 1936, vol. 116, p. 482.

Motors, convertors, commutators, rectifiers, etc.

A. ESAU and E. GOEBELER: *Zeitschrift für Hochfrequenztechnik*, 1928, vol. 31, p. 17.

K. HEINRICH: *Elektrotechnische Zeitschrift*, 1928, vol. 49, p. 1296; 1932, vol. 52, p. 1358; and 1935, vol. 56, p. 943.

C. V. AGGERS and W. E. PAKALA: *Electric Journal*, 1933, vol. 30, p. 423.

A. DENNHARDT: *Elektrotechnische Zeitschrift*, 1933, vol. 54, p. 419.

Elektroteknisk Tidskrift, May 1933, p. 419.

Siemens Zeitschrift, 1934, vol. 14, p. 67.

High-voltage transmission lines.

R. L. SMITH-ROSE: *Wireless World*, 1929, vol. 24, p. 476.

E. VAN ATTA and E. L. WHITE: *Journal of the American I.E.E.*, 1929, vol. 48, p. 682.

R. BRAILLARD: Paris H.T. Conference, 1933, Paper No. 102.

F. O. MCMILLAN: *Transactions of the American I.E.E.*, 1932, vol. 51, p. 385; *Electrical World*, 1933, vol. 102, p. 185.

H. H. BROWN: *Electrical Engineering*, 1933, vol. 52, p. 608.

P. SCHUEP and M. SOLLIMA: Paris H.T. Conference, 1933, Paper No. 82.

C. BRUNIAUX and R. PETIT: *Annales des Postes, Télégraphes, et Téléphones*, 1934, vol. 23, p. 222.

G. I. GILCHRIST: *Transactions of the American I.E.E.*, 1934, vol. 53, p. 899.

W. A. HILLEBRAND and C. J. MILLER: *ibid.*, 1934, vol. 53, p. 1213.

J. L. LANGTON and E. BRADSHAW: *Journal I.E.E.*, 1934, vol. 75, p. 643.

C. V. AGGERS and R. N. STODDARD: *Electric Journal*, 1934, vol. 31, pp. 305, 367.

E. A. SMITH: *Journal of the Franklin Institute*, 1934, vol. 218, p. 653.

A. DENNHARDT: *Elektrizitätswirtschaft*, Jan. 1935, p. 15.

K. VIEWEG: *ibid.*, Jan. 1935, p. 19.

M. DICK: *Bulletin, Association Suisse des Électriciens*, 1935, vol. 26, p. 192.

A. C. PRENTICE: *I.E.E. Aust., J.*, 1935, p. 1083.

Automobiles and aircraft.

H. DIAMOND and F. G. GARDNER: *Bureau of Standards Journal of Research*, 1930, vol. 4, p. 415.

L. F. CURTIS: *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20, p. 674.

J. JAFFRAY: *Comptes Rendus*, 1933, vol. 196, p. 609.

Wireless World, 1933, vol. 33, p. 18.

G. H. BROWNING and R. HASKINS: *Electronics*, 1933, vol. 6, pp. 273, 283.

Air Ministry Specifications D.T.D. G.E. 125, and E. & I., 442.

H. VIEHMANN: *Hochfrequenztechnik und Elektroakustik*, 1934, vol. 43, p. 85.

A. NEUBAUER: *ibid.*, 1934, vol. 44, p. 109.

W. B. SMITH: *Canadian Journal of Research*, April 1935, p. 508.

R. RUEDY: *ibid.*, Sept. 1935, p. 45.

Telephone systems, etc.

H. R. Fritz: *Telephony*, 1924, vol. 87, p. 18.

J. M. Duguid: *Bell Laboratories Record*, 1931, vol. 10, p. 124.

E. Rossberg: *Zeitschrift für Fermeldetechnik*, 1934, vol. 15, p. 85.

F. Seelemann: *Telegraphen- und Fernsprech- Technik*, 1935, vol. 24, p. 146.

Miscellaneous, medical apparatus, precipitators, furnaces, etc.

E. Goebeler: *Zeitschrift für Hochfrequenztechnik*, 1928, vol. 31, p. 20.

Elektrotechnische Zeitschrift, 1929, vol. 50, p. 855.

R. E. Boehler: *Electric Journal*, 1924, vol. 21, p. 422.

F. Müller: *Siemens Zeitschrift*, 1927, vol. 7, p. 6.

O. A. Redfern: *Radio Journal*, 1925, vol. 6, p. 25.

A. T. Lawton: *Radio Broadcast*, 1926, vol. 11, p. 299; 1927, vol. 12, p. 48; 1928, vol. 12, p. 217.

G. I. McKenzie: *Electric Light and Power*, 1928, vol. 6, p. 33.

(e) G.P.O. Reports

P.O. Radio Branch, interim report.

"Interference with Wireless Broadcast Reception by Tramway and Trolley-bus Systems," November, 1935.

Post Office printed pamphlets.

"Suppression of Radio Interference."

"Good Wireless Reception."

"Electrical Interference."

P.O. Radio Reports (not printed for publication).

No. 178: "The Investigation of Interference by Electric Lifts with Broadcast Reception."

No. 179: "The Investigation of Interference by High-frequency Electrical Therapeutical Apparatus with Broadcast Reception."

No. 192: "The Investigation of Interference by Mercury-Arc Rectifiers with Broadcast Reception."

No. 201: "Measurements of Impedance of a Heavy-current H.F. Choke at Broadcasting Frequencies."

No. 202: "The Further Investigation of Interference by Electric Trolley-bus Systems with Broadcast Reception."

No. 216: "Further Measurements on H.F. Choke Coils for the prevention of Interference by Trolley-buses with Broadcasting."

No. 255: "Measurement of the Interference from the Portishead-Bridgwater 132-kV Overhead Power Line."

No. 277: "Some Considerations relating to the Measurement of Radio Interfering Effects."

No. 295: "Measurement of the Impedance at Radio Frequencies of Post Office Condenser Units."

No. 300: "Further Considerations relating to the Measurement of Radio Interfering Effects."

No. 318: "Interference with Broadcast Reception caused by a Steel-tank Grid-controlled Mercury-arc Rectifier."

No. 321: "Theoretical and Practical Comparison of High- and Low-frequency Methods of Measurement of Radio Interference."

No. 332: "Comparison of the German Standard Radio-interference Measuring Equipment and the British Post Office Portable Measuring Set."

No. 346: "Prevention of Interference by Electro-medical Apparatus with Broadcast Reception."

W2. 187A: "Comparison of the E.R.A. and G.P.O. Radio-interference Measuring Sets."

(f) E.R.A. Reports

Ref. M/T22: "Classified Bibliography of Man-made Radio Interference and Associated Measurements."

Ref. M/T24: "Memorandum on American Proposals for the Measurement of Radio Interference."

Ref. M/T27: "Simplified Apparatus for Comparative Observations of Radio Interference produced by Electrical Appliances."

Ref. M/T28: "The Suppression of Short-wave Radiations from Automobile Ignition Systems."

Ref. M/T29: "The Suppression of Broadcast Interference from Trolley-buses."

Ref. M/T30: "Some Considerations in the Measurement and Suppression of Radio Interference."

Ref. M/T39: "The Magnitude of the Radio-frequency Disturbance from Trolley-buses and the Use of Condensers and other Devices in its Suppression."

Ref. M/T42: "The Suppression of Broadcast Interference from Electric Lifts."

Ref. M/T44: "The Properties and Performance of the E.R.A. Short-wave Receiver for Field-strength Measurements."

Ref. M/T45: "Methods of Measurement of Radio Interference."

Ref. M/T46: "A Note on the Representation of Rectification by a Fourier Series."

Ref. M/T47: "Short-wave Interference from Ignition Systems."

Ref. M/T48: "The Radio-frequency Disturbance from Mercury-arc Rectifiers and its Suppression."

Ref. M/T50: "Short-wave Radio Interference produced by Electrotherapy Apparatus."

Ref. M/T51: "Shocks from Unearthed Apparatus, with particular reference to Radio Suppression Devices."

Ref. M/T52: "The Suppression of Radio Interference with reference to Portable Appliances."

Ref. M/T53: "Relation between Sparking-Plug Current and the Short-Wave Radiation from Ignition Systems."

APPENDIX

Theory of Signal/Noise Ratio in Ideal Receivers

For the purpose of the present analysis it is assumed that the h.f. and l.f. amplifiers and associated equipment amplify uniformly all the components which lie within the frequency bands which they select. If this is the case, then the constant amplification factor may be omitted and it is only necessary to consider the effect of rectification and of the frequency-selection mentioned.

(1) Single interfering frequency.

The input voltage may be expressed as:—

$$V = P(1 + M\cos p_0 t)\cos(\omega + p)t + V_1\cos\omega t \quad (1)$$

where

P = amplitude of the broadcast carrier,
M = modulation depth,
$p_0/(2\pi)$ = modulation frequency,
V_1 = interfering voltage,
and $p/(2\pi)$ = frequency-difference between interfering voltage and carrier.

In the simplest form of ideal linear rectification all the half-waves of voltage of a given sign are faithfully transmitted while the half-waves of opposite sign are suppressed. Mumford and Stanesby* have represented this action very conveniently by the unit operator function:—

$$f(t) = \tfrac{1}{2} + P_1\cos\omega' t + P_3\cos 3\,\omega' t + \ldots \quad (2)$$

where $\quad P_n = (-1)^{\frac{1}{2}(n-1)}\dfrac{2}{n\pi}$

n being an odd integer.

This function is alternatively $+1$ and zero, with a mean period of $2\pi/\omega'$. Mumford and Stanesby regarded ω' as constant. This assumption is sufficiently accurate for the deduction of the main principle of interference measurement, but for greater certainty it is desirable at first to extend the analysis, since a combination of components of different frequencies does not necessarily give rise to a function of constant period and therefore ω' will usually vary in practice, giving a species of "frequency modulation." The two components of V can be regarded as vectors of angle ωt and $(\omega + p)t$, and the angle of the resultant is $\omega' t$, where

$$\omega' t = \omega t + \phi$$

and $\quad \phi = \arctan\dfrac{P(1 + M\cos p_0 t)\sin pt}{V_1 + P(1 + M\cos p_0 t)\cos pt} \quad (3)$

Forming the product $Vf(t)$, we have

Rectified voltage

$$= P(1+M\cos p_0 t)\cos(\omega+p)t\left[\tfrac{1}{2}+P_1\cos(\omega t+\phi)+\ldots\right] + V_1\cos\omega t\left[\tfrac{1}{2}+P_1\cos(\omega t+\phi)\ldots\right] \quad (4)$$

This expression gives a series of products which can be split up into summation and difference tones. Only those of low frequency will be accepted by the l.f. amplifier, so that terms involving ω or its multiples may be neglected. Thus the output due to V is given by:—

$$2V = PP_1(1+M\cos p_0 t)\cos(pt-\phi) + V_1 P_1\cos\phi \quad (5)$$

If $M = 0$, then

$$\frac{2V}{P_1} = (P^2 + V_1^2 + 2V_1 P\cos pt)^{\frac{1}{2}} \quad (5.1)$$

If M is not zero,

$$\frac{2V}{P_1} = P\cos(pt-\phi) + V_1\cos\phi + PM\cos p_0 t\cos(pt-\phi) \quad (5.2)$$

* A. H. Mumford and H. Stanesby: Radio Report No. 300 (P.O. Engineering Department).

The presence of V_1 multiplies the modulation term $(M\cos p_0 t)$ by a factor $\cos(pt-\phi)$, where

$$\cos(pt-\phi) = \frac{V_1\cos pt+P(1+M\cos p_0 t)}{\left[V_1^2+2PV_1(1+M\cos p_0 t)\cos pt+P^2(1+M\cos p_0 t)^2\right]^{\frac{1}{2}}}$$
$$= \frac{V_1\cos pt+P(1+M\cos p_0 t)}{\left[V_1^2+P^2(1+M\cos p_0 t)^2\right]^{\frac{1}{2}}}\left[1+\frac{2V_1P(1+M\cos p_0 t)\cos pt}{V_1^2+P^2(1+M\cos p_0 t)^2}\right]^{-\frac{1}{2}}$$

Neglecting M,

$$\cos(pt-\phi) = \frac{V_1\cos pt+P}{(V_1^2+P^2)^{\frac{1}{2}}}\left\{1+\left[\frac{2V_1P\cos pt}{V_1^2+P^2}\right]^{-\frac{1}{2}}\right\}$$
$$= \frac{V_1\cos pt+P}{(V_1^2+P^2)^{\frac{1}{2}}}\left[1-\frac{V_1P\cos pt}{V_1^2+P^2}+\ldots\right]$$
$$= \frac{P}{(V_1^2+P^2)^{\frac{1}{2}}}+\frac{V_1\cos pt}{(V_1^2+P^2)^{\frac{1}{2}}} - \frac{V_1P^2\cos pt}{(V_1^2+P^2)^{\frac{3}{2}}}-\frac{V_1^2P\cos^2 pt}{(V_1^2+P^2)^{\frac{3}{2}}}$$
$$= \frac{P}{(V_1^2+P^2)^{\frac{1}{2}}}-\frac{V_1^2P}{2(V_1^2+P^2)^{\frac{3}{2}}} + \cos pt\left[\frac{V_1}{(V_1^2+P^2)^{\frac{1}{2}}}-\frac{V_1P^2}{(V^2+P^2)^{\frac{3}{2}}}\right]$$

and terms in $2pt$, $3pt$, etc.

If P^2 is neglected as compared with V_1^2 in the first two terms,

$$\cos(pt-\phi) = \frac{P}{2V_1}+\cos pt\left\{\frac{1}{\left[1+(P/V_1)^2\right]^{\frac{1}{2}}}-\frac{(P/V_1)^2}{\left[1+(P/V_1)^2\right]^{\frac{3}{2}}}\right\} \quad (6)$$

Since ϕ depends on V_1, P, and M, the "normal" terms $P\cos(pt-\phi)$ and $V_1\cos\phi$ give rise to modulation products. This form of distortion is a second-order effect in most instances, and is neglected in the classical analysis. It is also neglected here, where we have only followed the transformation of the normal modulation tone from the point of view of its amplitude, without considering its distortion in any detail.

The first term represents the apparent decrease of modulation caused by the presence of another carrier, the "demodulation effect."* The second term represents the intermodulation between V_1 and the sidebands of P, which is only affected to the second order by the carrier of P.

If P is large compared with V_1, ϕ tends to (pt), i.e. ω' corresponds to the carrier frequency, and

$$\frac{2V}{P} = PM\cos p_0 t + V_1\cos pt - \frac{3}{4}\left(\frac{V_1}{P}\right)V_1\cos 2pt + \ldots \quad (7)$$

$$= PM\cos p_0 t + V_1\cos pt \text{ (approx.)}$$

Thus the interfering voltage V_1 appears undisturbed in the output but with its frequency changed to the

* For the classical analysis of this effect, see E. V. Appleton: *Wireless Engineer*, 1932, vol. 9, p. 136; and F. M. Colebrook: *Wireless World*, 1931, vol. 28, p. 560.

difference between the original value and the carrier frequency. The signal/noise ratio is thus MP/V_1 if both are observed in a similar manner.

(2) Several interfering frequencies.

For convenience, let the broadcast signal be

$$P(1 + M \cos p_0 t) \cos \omega t$$

Then $\omega' t$ is, as before, $(\omega t + \phi)$, where

$$\phi = \arctan \frac{\Sigma a_k \sin (p_k t + \alpha_k)}{P(1 + M \cos pt) + \Sigma a_k \cos (p_k t + \alpha_k)} \quad . \quad (8)$$

provided the summation includes all the interfering voltages like

$$a_k \cos [(\omega + p_k)t + \alpha_k]$$

which lie in the band accepted by the receiver.

Equation (5) now becomes:—

$$\frac{2V}{P_1} = P(1+M \cos p_0 t) \cos \phi + \Sigma a_k \cos (p_k t + \alpha_k - \phi) \quad (9.1)$$

If P is large compared with the interfering voltages, e.g. if the ratio is greater than 20 or 30 db.,

$$\sin \phi = \frac{\Sigma a_k \cos (p_k t + \alpha_k)}{P(1 + M \cos p_0 t)}, \text{ and } \cos \phi = 1 \quad . \quad . \quad . \quad (9.2)^*$$

Thus

$$\frac{2V}{P_1} = PM \cos p_0 t + \Sigma a_k \cos (p_k t + \alpha_k) + a_k \sin (p_k t + \alpha_k) \frac{\Sigma a_k \sin (p_k t + \alpha_k)}{P(1 + M \cos p_0 t)}$$

Considering the summation term, it is clear that the amplitude of each component is only affected to the second order, since $\Sigma a_k/P$ is small. If the first order of small quantities is neglected, then

$$\frac{2V}{P_1} = MP \cos p_0 t + \Sigma a_k \cos (p_k t + \alpha_k) \quad . \quad (9.3)$$

The signal/noise ratio is the ratio of the first to the second of these terms. If the noise is removed, then the signal is correctly measured; and if the modulation is removed, there remains

$$\Sigma a_k \cos (p_k t + \alpha)$$

which gives the noise correctly. Again, in the absence of a carrier, the h.f. interference is:—

$$\Sigma a_k \cos [(\omega + p_k)t + \alpha_k]$$

and it is therefore immaterial whether the h.f. interference in absence of a carrier is measured or the l.f. noise with a carrier is measured, provided a similar voltmeter is employed and provided that $1/\omega$ is much less than $1/p_k$ and much less than the charging time-constant of the voltmeter, and also that

$$\Sigma a_k \cos (p_k t + \alpha_k)$$

is continuous near its maximum value. If an acoustic filter is incorporated in the l.f. voltmeter, then the selectivity curve of the h.f. voltmeter must be correspondingly modified, but the time-constants should be the same. It is essential that the h.f. band should be correctly selected in the h.f. method, but in the l.f. method some of the selection may be made after rectification without important error, although it is desirable that the selectivity should be attained on the h.f. side. If the spectrum were continuous and uniform, all the a's would be equal and the p's would be in arithmetic progression. If, further, the phases were equal or completely incoherent in time, the magnitude of the interference would be proportional to the band width or integral of the selectivity curve. Since these conditions usually hold, it is possible to correct for a non-standard band-width by a simple multiplying factor.

If the interfering voltage is not small compared with the carrier, the output can be obtained by expanding (9.1), and a complicated form of distortion results. It has already been noted that, to a first approximation, the amplitude of the noise terms is unaffected, a phase variation being superposed, so that the error at first increases only slowly with the relative magnitude of the interference.

If there is no carrier, P is zero and only the second term of (9.1) remains. From (8) it is seen that ϕ will pass through the various values $(p_k t + \alpha_k)$ in turn, so that the resulting noise will contain all the intermodulation tones corresponding to the value of $(p_n - p_k)$. Thus the character of the noise is changed from that when the carrier is present. However, if the spectrum is continuous, the same frequency band will be covered, but the distribution will be different, since, other things being equal, the number of intermodulation products of a given frequency increases proportionately to the difference between the upper frequency-limit of the l.f. band and the frequency under consideration. Thus a filter giving such a weighting might be an advantage.

Since the standard voltmeter is largely a peak voltmeter, it is of interest to consider the peak value of the interference in absence of a carrier. From (9.1),

$$\frac{2V}{P_1} = \Sigma a_k \cos (p_k t + \alpha_k - \phi) \quad . \quad . \quad (10)$$

$$\phi = \arctan \frac{\Sigma a_k \sin (p_k t + \alpha_k)}{\Sigma a_k \cos (p_k t + \alpha_k)}$$

Choose the origin for time such that

$$\sum_0^{n_0} a_k \sin \alpha_k = 0 \quad . \quad . \quad . \quad . \quad (11)$$

That is,

$$\sum_0^{n_0} x_k = 0$$

over the range selected.

Let k be proportional to the frequency of the component, i.e. p_k is proportional to k, a hypothesis which is usually legitimate. Then, by analogy with the integral of a product,

$$\sum_0^{n_0} k x_k = n_0 \sum_0^{n_0} x_k - \sum_{k=0}^{k=n_0} \sum_0^{k} x_k = -\sum\sum x_k$$

* Neglecting the constant term.

from (11), provided n_0 is large. Now if x_k is distributed at random, then $\Sigma\Sigma x_k$ has a most probable value of zero. Thus

$$\Sigma k x_k \simeq 0 \simeq \Sigma p_k a_k \sin x_k \quad . \quad . \quad . \quad (12)$$

Now as $t \to 0$, $\phi \to 0$, from (11). Thus

$$\frac{-2V}{P_1} \to \Sigma a_k \cos \alpha_k$$

But, since (12) is a most probable condition,

$$\left[\frac{\partial}{\partial t}\Sigma a_k \cos (p_k t + \alpha_k)\right]_{\to 0} \simeq 0 \quad . \quad (12.1)$$

That is,

$$\Sigma a_k \cos (p_k t + \alpha_k)$$

has probably its maximum value, while it can similarly be deduced that in the same conditions (10) has an equal probability of a maximum value. It may therefore be said that, provided the number of lines in the noise spectrum is large and the distribution of phases and amplitudes is random, the most probable condition is that the noise either in presence or in absence of a carrier will have the same peak value and is therefore likely to give the same reading on the voltmeter employed. It is not easy to place an absolute value on this probability, but the deduction as regards this general case is reinforced by the experimental fact that the carrier makes little difference in a large number of instances where the interference is of a more or less continuous nature. If the phases and amplitudes are equal a similar conclusion can be reached in a simpler manner.

Consider the simple but frequent case of a square pulse where all the components near a given frequency ω have the same amplitude and phase, while $p_k = k_p$, since the interval between successive components is constant. Thus

$$\phi = \arc\tan \frac{\Sigma \sin kp_0 t}{\Sigma \cos kp_0 t} \quad . \quad . \quad . \quad (13.1)$$

whence

$$\begin{aligned}\frac{2V}{P_1} &= a\left[(\Sigma \cos kp_0 t)^2 + (\Sigma \sin kp_0 t)^2\right]^{\frac{1}{2}} \\ &= a \text{ mod.} \Sigma e^{jkp_0 t} \\ &= a \text{ mod.} \left(e^{jp_0 t}\frac{1 - e^{jnp_0 t}}{1 - e^{jp_0 t}}\right) \\ &= a\left(\frac{1 - \cos np_0 t}{1 - \cos p_0 t}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad (13.2)\end{aligned}$$

where n is the number of components selected in the band width.

The maximum value of $2V/P_1$ is given by $t = 0$ and is found by determining the limit of (13.2), which is na. Similarly, the maximum value of

$$\Sigma a \cos (pk + \omega)t$$

is na, so that the l.f. voltmeter without a carrier will give an approximately correct measure of the interference.

It is clear that, in general, errors will arise from the omission of the carrier. These errors may be of either sign, but in practice the curvature of the actual detector characteristic exercises a general determining influence, such that with the carrier present the measured noise is greater, since the rectifier is operating over a straighter and more sensitive portion of its characteristic.

DISCUSSION BEFORE THE WIRELESS SECTION, 6TH APRIL, 1938

Mr. A. H. Bennett: Some impatience has been expressed in the radio, the technical, and the semi-technical Press on the subject of radio interference. Some people have thought that the electrical industry and the radio industry should have cured interference long ago; but it is a very complex problem, and many interests have to be brought into line before a solution can be reached. Great Britain is as near the desired result at the present time as probably any country in Europe.

I am glad to be able to report from several sources that since the trolley-buses were put into service in North London, approximately 3 weeks ago, the amount of radio interference has been greatly reduced. There has been a certain amount of interference caused by the tramways, but the trolley-buses are relatively free.

Mr. F. M. Colebrook: I notice that the authors use the term "mains attenuation" as an alternative to "coupling factor."* "Mains attenuation" has a fairly definite meaning, quite different from that implied in this paper, and I therefore prefer the use of the term "coupling factor." I hope that this term will be employed in future if either of the terms comes into common use.

* Corrected for the *Journal*.

Mr. R. T. B. Wynn: I cannot believe that there can be real contention on the question of who is responsible for silencing interference. The broadcasting service must do its part in trying to make things a little easier for the other sections of the electrical industry, and vice versa. It is frequently stated that a great many listeners have decided to come on to the public supply mains because they want to use all-mains receivers. If they do, they become a market for electrical appliances, which they will expect to be interference-free. I should like to quote two figures which may be of interest. Sir Felix Pole said recently that approximately 35 % of the householders in this country are not yet connected to public supply mains. The number of homes without wireless licences is about 33 %. There is a similarity between these two figures which points to a rather obvious moral.

It may cause great confusion if the B.S.I. "interference-free" mark becomes optional. If Mrs. A is very keen on listening and wants to buy a sewing machine, she may think that she could not use it when listening, and therefore need not pay the extra half-guinea for the two condensers. But she would be very angry if Mrs. B were to think the same about her violet-ray machine.

On page 346 of the paper it is stated that "the signal

(programme)-to-noise ratio so determined as corresponding to the limit of toleration was then found to be substantially independent of the observer, type of programme, and type of noise. . . ." It is agreed that there is only one way to measure the strength of the wanted signal and that is to measure the peaks, because mean modulation in a broadcasting programme is so indefinite. Attempts to measure mean modulation have led into all sorts of difficulties, because, for example, we do not know whether to include the time when the orchestra is having a rest between two movements. There are other and less obvious factors to be considered, including the reverberation of the studio. Certain programme producers actually use reverberation to get more of a sense of climax without exceeding the peak modulation levels.

I believe that the degree of tolerable interference is dependent on the type of programme, and must be set at a ratio which will satisfy the most difficult items. There are certain programmes, such as a full symphony orchestra, which demand all the dynamic range that can be given to them. This must mean that the peaks occur less frequently, and therefore a given ratio of interference based on peak modulation must sound worse. The problem is made particularly serious by the type of audience which is attracted by such programmes. Symphony-concert audiences go through long periods of very low modulation, during which they are listening very intently indeed, even when the orchestra is not playing, in a pause between two movements. I should like the authors to give a little further explanation for their statement that an acceptable interference ratio is independent of the type of programme. I hope that they mean the ratio must be set at a level which will satisfy all types of programme.

Mr. T. H. Kinman: I find that it takes 6–8 weeks to train an operator in the technique of using the interference measuring set shown in Fig. 2. It is not simply a matter of reading a meter or turning a knob, but of interpreting the measurement, and the ability to do this can come only with experience. The point that I want to make is that if it becomes necessary to equip every factory with such precision apparatus, there may be difficulties in finding suitable personnel to operate the testing equipment.

I am surprised that the authors do not mention in Section (2) such potential sources of interference as the radio installation itself, domestic lighting and power circuits, earthing conductors (when used), terminal and fuse boards, lamps and lamp fittings, and plugs and sockets. All these items are frequent sources of interference of a most elusive and annoying type, and I think that much could be done to remove such causes of interference by the more strict observance of the regulations, including the I.E.E. Wiring Regulations. Some radio-interference statistics recently published in America showed that in a certain State no fewer than two-thirds of the complaints arose from items on the listeners' own premises, and many of the items were of the sort to which I have referred.

The details given on page 380 regarding the distribution of interfering sources might have been made somewhat more informative, and certainly more up-to-date; for instance, the term "motors" covers a very wide range, from about 50 watts upwards.

The authors treat very lightly the question of what can be done to correct the appliance itself before additional suppression is added. Practically every type of apparatus could be improved by some change in design or assembly, whereby any additional suppression required would be rendered easier and less costly. Even more important is the need for investigation into the many causes of the wide variations observed now in terminal interfering voltages on different samples of apparatus of a particular type, which makes it difficult to suppress to a common denominator. I say this because the authors imply that certain rules can now be used for dealing with the smaller items.

Mr. E. M. Lee: I want to refer to the figure of 500 μV that is laid down in Clause 2(*a*) of B.S.S. No. 800—1937. I have heard it suggested, particularly abroad, that we are being rather too ambitious; for the long wave band where it is most difficult and most expensive to apply suppression, there is a suggestion on the Continent that the figure should be 1 500 μV up to a maximum wavelength of 2 000 metres. There is not so much difference between our figure and the Continental suggestion as may at first appear, because our 500 μV applies up to a maximum wavelength of 1 500 metres, and is therefore equivalent to about 1 000 μV at 2 000 metres.

We should give the present standard a good trial before there is any question of reconsidering it or allowing any tolerance. One of the authors' slides showed that 64 % of earthed machines—i.e. machines in the most difficult condition—can be suppressed with condensers alone to 200 μV asymmetric voltage. With such a standard of suppression the worst of the machines with their worst adjustment after some years of wear would still give a figure of about 500 μV. I think that those prescribing suppression should purposely put machines out of adjustment, getting the brushes in the worst possible condition so as to imitate the state of affairs when the machine is rather old, and then try to keep below 500 μV.

We have the difficulty that about one-third of the machines when earthed will not be suppressible with condensers alone. Some electrical designers, when confronted with B.S.S. No. 800—1937 as recently as November last, tried the experiment of fitting condensers and did not immediately get the required suppression. I would point out that suppression engineers who have been doing nothing else for 4–5 years sometimes have to work for days to find a way of getting down to the required level, but once the trick has been discovered for a particular machine it holds good for that machine. A skilled suppression engineer would not feel that his task was complete unless he turned out his sample machine with a level of 50 or 100 μV over a wave band far beyond the coverage of the present Specification; for, it is usually very little more difficult to extend the range down to the short and ultra-short wave bands.

To make suppression most successful one must reduce the length of the condenser leads to $\frac{1}{4}$ in. if possible; often a reduction from $\frac{1}{2}$ in. to $\frac{1}{4}$ in. avoids the use of chokes. The use of a suppressor in a flexible lead is only a temporary expedient to be employed until the manufacturer finds it convenient to re-design and put his condensers where they ought to be, namely inside the casing.

Mr. G. A. Struthers: One curious feature of the

authors' results is the great amount of difference in the levels of interference produced by different machines. For example, with vacuum cleaners of more or less the same horse-power and design we get interference varying from 2 mV to 100 mV. Some of the more expensive machines give far more interference than the cheaper ones; actually, the most expensive vacuum cleaner which the Post Office ever tested had the highest level of interference.

It would be worth while to investigate the reason for the disparity which exists between machines of different makes, and also between individual machines of the same design and made in the same way. If we confine our attention to a single type of motor, there seem four possible reasons for this disparity; namely the number of commutator segments, the electrical balance of the windings, the mechanical balance of the machine, and, in the larger machines at least, possibly the question of lubrication. Many portable vacuum cleaners are already too heavy, and if anything could be done—e.g. by changing the type of motor or improving the design—to avoid the need for suppressors, it would be of tremendous help to the people who have to use the machines.

Mr. E. A. Watson: I should like to deal with the question of ignition interference from motor-cars.

Such ignition interference is primarily a question of interference with ultra-short-wave systems. The motor-car does not interfere with ordinary broadcast reception, and I do not think the paper is intended to deal with the question of the suppression of the ignition equipment of the motor-car for the sake of any radio receiver which is carried on the car itself. The suppression of the interference which the motor-car may cause to short-wave systems in the neighbourhood will therefore involve fitting suppression devices to every motor-car in the country, a very difficult matter involving, I should estimate, a capital outlay of about £2 000 000.

The authors mention various methods of suppression. The ordinary method of braiding and bonding which is used on aeroplanes is particularly difficult to apply to a motor-car. On an aeroplane, which normally runs on full throttle, one operates with relatively short plug-gaps and as the plug temperatures are invariably high in addition the plug voltages are relatively low, of the order of 5 kV or less; but on a motor-car, which has to work over wider ranges of throttle opening with larger plug-gaps and in general lower plug temperatures, considerably higher voltages (some twice as great or even more) are necessary. These higher voltages may lead to a good deal of insulation leakage and, still worse, to insulation deterioration and breakdown, while the increased energy required by the capacitance of the braiding may lead to troubles of various sorts in both primary and secondary circuits. Fortunately, as the authors point out, in most cases complete suppression will not be necessary, and in many cases resistances in the leads will suffice, but it is not yet certain whether resistances can be used on all motor vehicles without their having some effect on the performance of the engine; and the public, while being quite willing to go to some trouble and expense to avoid interference on short-wave reception, may not be inclined to install equipment which adversely affects the running of their motor-cars.

A great measure of improvement can be obtained if the coil is mounted on the engine, but unfortunately the present-day motor-car manufacturer mounts his engine on rubber to make it sweet-running and then takes advantage of the rubber mounting by making the engine "rough," so that it vibrates to a serious extent. It is rather unfair to expect a delicate apparatus, which has to deliver a voltage up to 10 000 volts, to be mounted on a crankcase at temperatures up to 100° C. and to be shaken about violently and yet to have an indefinite life without being given any attention. While, therefore, the automobile engineer is cognizant of the requirements and of the need for avoiding unnecessary interference with short-wave reception, I would wish to make it clear that the solution of the problem is not in all cases quite so simple as would appear at first from the paper.

Mr. E. C. S. Megaw: I should first like to make some remarks on the subject of motor-car ignition interference. This interference reaches a maximum at frequencies of the order of 25–50 Mc./sec., i.e. in the neighbourhood of the present television bands. We have found that the general level of interfering field-strength from motor-car ignition systems at frequencies of 300–600 Mc./sec. is much lower, probably 20–30 db. below the level at frequencies of about 50 Mc./sec. The dependence of ignition interference level on frequency is thus a factor to be considered in planning future short-range radio services.

The rest of my contribution is concerned with the interference from electrical therapy machines in the ultra-short wave band. The use of ultra-short waves for such purposes is increasing fairly rapidly, and for reasons which are partly medical and partly economic the wavelength of 6 m. has become the prevailing standard for much of this work. So far as spark apparatus is concerned there is very little to be done except to adopt the most complete screening possible. In the case of valve apparatus, which in this field, as in the field of communication, is gradually displacing spark apparatus, the problem is essentially simpler because the radiation is confined to relatively narrow frequency bands. Table A gives some data on the effects of different kinds of screening on the radiation from a 6-m. valve therapy machine. In one test a complete copper-sheet-screened room was tried in which the electrical continuity was as perfect as possible; special methods were used to seal the door, and there was complete filtering of the mains supply leads. Two methods were used—a completely screened isolation transformer and a special condenser filter. The latter, employing a pair of cylindrical condensers of very low residual inductance, was quite as effective as the isolation transformer, and much cheaper. Another device which was tried was to place a strip of copper foil round the load circuit of the machine, with the idea of limiting and partially short-circuiting the radiation field. Although we tried several variants of that scheme, it was not very successful; but it might be useful for reinforcing the other methods of screening. Some rough measurements which we made of the field strength from a 6-m. electrotherapy machine at a distance of the order of 10 yd. come within 10 db. of the values in Curve A of the authors' Fig. 13, which is a very plausible agreement. Even with the best possible kind of screening, and the best possible mains

filtering, if the radiation from a valve machine of about 0·5 kW output lies within the television frequency band, and there is a television receiver in the same building, there will in almost all cases be appreciable interference. On the other hand, if the frequency of any valve machine is outside the television band, the problem of eliminating interference is enormously simplified and the solution is quite cheap; in some cases no screening at all is necessary if mains filtering is provided. We found that mains filtering is always essential. In this connection it would be interesting to know the frequency of the valve set used in the authors' demonstration.

In connection with the question of frequency spacing the properties of the radiated signal are of importance. Our measurements showed that very roughly the frequency band occupied by a 6-m. valve set working on unrectified a.c. anode supply is about $\pm 1\%$ from the carrier frequency. The attenuation to which that corresponds is probably between 40 and 60 db. The frequency-change of such machines on heating-up was in our sets less than 1 %. Changes due to alteration of the load circuit depend very greatly on the design of the machine, but need not exceed 1 % or 2 %, so that in order to avoid interference completely a frequency-spread of the order of a few per cent should be allowed.

We have now to face the situation in which a large number of diathermy machines are operated on a nominal frequency of 50 Mc./sec. (How nominal that figure sometimes is can be realized from a case which the authors quote where a so-called 6-m. set gave a fundamental frequency coinciding with the vision transmission from Alexandra Palace.) If we can agree that the manufacturers of such machines will confine their frequency to a specified band—a tentative figure of 48 to 52 Mc./sec. occurs to me as reasonable, but closer limits have already been adopted by the manufacturers with whom I am associated—and, on the other hand, if the designers of television services will regard such a band as occupied in making plans for future transmitters, interference between apparatus of this kind and television can be completely avoided. On the other hand, if no such arrangement is made, limiting by agreement the present legal rights of both parties, this kind of interference is likely to be a serious and increasing embarrassment to the development of television.

Table A

ATTENUATION OF RADIATED FIELD FROM A 6-M. 0·3-KW VALVE THERAPY MACHINE BY SEVERAL TYPES OF SCREENING ENCLOSURE: DISTANCE APPROXIMATELY 10 YD.

Type of screening	Attenuation (db.)	Mains filter
(1) Copper sheet, electrically continuous; door clamped to give contact all round	60	Completely screened isolation transformer, *or* special condenser filter ($2 \times 0\cdot006\ \mu F$)
(2) As (1)	18	None
(3) " Fine " copper mesh (about 150 to the square inch), joints overlapped 1 in. and soldered at about 3-ft. intervals. Screening on door makes contact with main screen, though less perfectly than in Case (1)	30	Partially screened isolation transformer
(4) " Medium " copper mesh (about 12 to the square inch), joints not soldered, window not screened	14	None (receiver and oscillator supplied from same mains)
(5) As (4), but with window screened	25	None (receiver out of doors and supplied from separate source)
(6) Copper-foil strip 5 in. wide surrounding patient circuit and load, spaced about 6 in. from patient-circuit leads and earthed to metal frame of oscillator	7	Partially screened isolation transformer

Mr. W. Hill: In common with Mr. Kinman, I am very surprised at the figures for the distribution of interfering sources given on page 380, and particularly at the last two items. In my experience, house wiring is a much more common cause of interference than is there indicated. Do the authors include refrigerator motors under the general heading " motors "? I have found these motors among the most troublesome items to deal with.

With regard to what the authors say on page 353, have they had experience of the use of insulators on power lines with a metallized coating? These have been very successful in America. A comparison of insulators on a surface-resistance basis gives an indication as to which one is going to effect a cure of radio interference, and I recommend also the use of the high-frequency test. Many insulators have proved faulty on that test which can stand up to the ordinary dry and wet flashover test and yet be the cause of radio interference. For locating

any faulty insulator we have found the Tebo stick most reliable and easy to operate. In one case which came to my notice recently, it was suggested that there was a faulty insulator on a 33-kV overhead line some 6 miles away from the wireless set which was giving trouble. The interfering voltage was supposed to be transmitted along the 33-kV line and through the transformer; but I did not believe this possible. I would ask the authors whether interference from a faulty insulator on a 33-kV line can be transmitted through the transformer. I should have thought that the impedance of the transformer would have been too high and would have choked any high-frequency operation. The fault was finally located on the wiring next door!

I should like to ask whether an increase in the current being transmitted on an e.h.t. power line does not cause an increase in the level of radio interference when this is present.

Mr. E. L. E. Pawley: It is astonishing how little is known about the efficiency of receiving aerials. One would have supposed that every elementary textbook would give a chart showing the effective height and the impedance to be expected from every shape and size of receiving aerial, whether indoor or outdoor, with or without screened down-leads; but that is not the case. We know just what it would cost us to give 1 db. more output from Droitwich, and the manufacturers know more or less what it would cost them to suppress the interference from a machine by 1 db.; but the listener has not the remotest idea what he must do to improve the signal/noise ratio by 1 db.

Mr. Watson spoke about motor-car ignition systems not affecting ordinary broadcast reception; he must have been referring to broadcast reception on medium and long waves, because interference of this type can be very severe on short-wave broadcast reception. As regards interference with television, the authors give some figures for the signal/noise ratio which has been found tolerable; but I would point out that the figure which can be tolerated depends very much on the nature of the picture, the type of interference, and the part of the picture which it affects.

There is still a great deal of work to be done in making more complete our information on interference at the higher frequencies.

The education of the listener and of the general public in the matter of radio interference is of vital importance. In particular, listeners must be encouraged to use efficient aerials, and landlords must be asked not to put unnecessary restrictions on the aerials which their tenants are allowed to erect.

With regard to Fig. 7, is it an accident that the maximum interference on the long wave band coincides precisely with the wavelength of Droitwich? The scale of ordinates gives levels in decibels above the level at 200 kc./sec., and, this being so, I should like to know why the lower curve does not intersect the zero line on the decibel scale.*

Fig. 8 gives some useful figures of interference at certain frequencies caused by trolley-buses, and I hope it will be possible one day to extend that information to other frequency bands.

* Since corrected for the *Journal*.

On page 367 appears the statement: "For example, if in a given case the effective height of aerial was 1 m. and the mains attenuation was 37 db., a field of 1 mV per metre would be adequately protected from mains-borne radiation." Now if one refers to Fig. 25 to find out just what that "if" means, one finds that in less than 20 % of cases is the mains attenuation actually 37 db. or more; in all other cases it is less. Fig. 23 shows that the effective height is 1 m. or more in only 70 % of the cases, leaving 30 % which will get a weaker signal than the authors bargain for. Multiplying those two probabilities together, one finds that an alarming percentage of our 8 million listeners may still be in a position to complain about interference, even when the limit laid down in B.S.S. No. 800—1937 is everywhere complied with.

Mr. J. S. Forrest: I shall confine my remarks mainly to interference due to high-voltage overhead power lines. It is convenient to divide this type of interference into two main classes: (1) interference due to abnormal conditions in the power network; and (2) interference under normal operating conditions when the overhead lines and associated equipment are in perfect working order.

Abnormal interference is due to a fault on the power system causing a discharge which generates radio-frequency energy. The disturbance may be propagated throughout the power system, thus giving rise to widespread interference. In such cases, however, it is usually a simple matter to locate the fault and cure the interference.

The type of interference which occurs under normal operating conditions represents a much more serious problem. The cause is discharges on the line insulators, either on the surface of the porcelain or between the porcelain and the conductor or insulator hardware. There is at present no complete cure for this form of interference, and it must be recognized that there is a certain minimum level of interference which is inseparable from the operation of a high-voltage overhead-line system. In the case of lower-voltage (e.g. 33 kV) lines, which are usually insulated with pin-type insulators, it is possible by using special types of insulator to reduce the interference. The most successful type of insulator has a very low capacitance so that the energy in the spark discharges is reduced, with a consequent reduction in the interference. It is not possible at present to effect any further improvement in the performance of the chains of cap-and-pin insulators employed on the highest-voltage lines.

The characteristics of this type of interference are well illustrated by the data given in the paper. For example, from Fig. 9 it will be seen that the interference decreases as the wavelength decreases, and it may be mentioned that it is quite possible to listen to 20-m. American broadcasting within a very short distance of 132-kV transforming stations. Similarly, the results given in Fig. 10 are borne out by practical experience; it is usually found that, at distances of more than 50 yd. from the transmission line, interference with broadcasting is quite negligible. The results recorded in Table 4 are also borne out in practice, as complaints of interference are received only under humid weather conditions. Incidentally, the most prolific sources of complaints are the newly developed housing estates in which the houses are built under the power lines. It is considered that in

such cases the builder should provide a screened aerial system for the benefit of the tenants.

In Fig. 11 it is indicated that the attenuation along the line is very small, and this suggests that the interference at mid-span would not differ appreciably from that at the tower. I should like to know whether the authors have made any measurements which confirm this.

With regard to mercury-arc rectifiers, large installations of rectifying equipment may give rise to interference with receivers connected to the a.c. mains associated with this equipment. The rectifiers distort the a.c. voltage wave, the distortion usually taking the form of the introduction of 5th and 7th harmonics, and these are propagated throughout the a.c. system associated with the rectifiers and affect radio sets which are not provided with particularly efficient smoothing equipment.

It is satisfactory to note that overhead power lines are responsible for only 2 % of the cases of interference referred to on page 380, particularly as there is no practicable means of suppression of interference of this type. Regarding the investigation of power-line interference, it has been found that the most convenient equipment consists of a standard car radio with an output meter and a switch to cut out the automatic volume control.

Captain J. McVicar: What is the relative effectiveness of galvanized-wire netting and expanded metal for screening purposes, and what size of mesh of expanded metal corresponds to the $\frac{1}{4}$-in. galvanized netting mentioned in the paper? I should also like to know how far double screening is effective, and whether there is an optimum distance between the two screens. From the point of view of construction it is easier to have the screens close together, say within $\frac{1}{2}$ in. of each other, and this practice should be adopted if it gives nearly as effective suppression as is obtained with the screens, say, 6 in. apart.

Finally, there are two practical points which I should like to put. In the case of the window with mesh in the glass, how are the ends of the wire which come out of the glass bonded? Does the means employed ensure that water cannot get to the mesh as it emerges from the glass? I have come across an interesting case of a piece of wired glass which was cut with a little mesh coming out from the ends; it was left out of doors for 3 weeks, and by the end of that time, at the point of emergence from the glass, the wire was corroded completely through. Have the authors any experience of the life of wire netting embedded in plaster? I imagine that with certain types of plaster there will be no wire netting left after a few years, unless precautions are taken.

Mr. F. R. W. Strafford: On page 364 the authors erroneously describe the mechanism of the effect whereby radio interference is produced by neon signs. This type of interference is nothing more than a relaxation oscillation of a type similar to that produced by ordinary gas-discharge devices associated with television time-bases. In the simplest time-base circuit a gas-discharge tube is connected across a capacitance, and this parallel arrangement is charged from a d.c. source of supply through a suitable resistance. Owing to the difference between the striking and extinction voltages of the gas, this resistance-capacitance combination will give rise to an oscillation whose wave-form is substantially sawtoothed in shape. Now the equivalent circuit of a neon sign is very similar to this arrangement excepting that the d.c. supply isreplaced by an a.c. source, the resistance is the equivalent series resistance of the high-voltage transformer, and the capacitance is the capacitance of the screened cable used for connecting the high-voltage transformer to the sign electrode.

In earlier laboratory investigations I failed to reproduce the interference solely because I had omitted to include the high-capacitance cable in the circuit. Unbonding of the shielding of this cable will in all cases reduce the interference to zero, unless, of course, the unbonding is accompanied by corona and other leakage effects.

Referring to the question of radiated interference, I feel a little worried about the constant use of the term "radiation" in connection with fields of interference which exist close to an interfering item. At a distance of less than 10 yd. from an interfering item the fields are obviously electric (scalar) or magnetic (vector) induction fields, and as such cannot be referred to in terms of volts per metre.

I am pleased to note the remark on page 379 that certain all-wave aerials with an unscreened twisted down-lead have no anti-interference properties on medium and long waves since their equivalent circuit is that of an ordinary T aerial. There have been so many instances of deceptive advertising claims in this respect that an authoritative announcement is welcome.

Mr. O. E. Keall (*communicated*): Referring to the theory of the signal/noise ratio in ideal receivers, given in the Appendix, it would appear that the application of the unit operator function $f(t)$ of equation (2) to a signal or signals determines the average value of the voltage of the unidirectional pulses of high-frequency energy obtained as a result of rectification. This may differ appreciably from the audio-frequency output voltage obtained in practice since the analysis takes no account of the detector load (or, alternatively, assumes a load without time-constant).

This omission may result in an estimate of signal and noise outputs differing appreciably from the actual output at the detector load terminals. For instance, the behaviour of the detector and its load at the beat frequency $p/(2\pi)$ is of some importance, for if the time-constant of the load (or the beat frequency, whether outside or inside the audio spectrum) is such that the detector cannot follow the beat-frequency variations, the noise will be much reduced and demodulation will not occur, with the result that actually a better signal/noise ratio is obtained than is indicated by the theory.

I would draw attention to an error in the last term of equation (4), which should read $P_1 \cos(\omega t + \phi)$.*

Mr. H. K. Robin (*communicated*): The paper contains no reference to the suppression of interference at the receiver, other than a brief description of all-wave antenna systems. The type of interference to which I refer is that which persists when the aerial has been removed and the receiver left at full sensitivity. I have been associated with some measurements on this type of interference, and would put forward the following description and results for the comments of the authors.

The mains interference voltage is considered to exist

* Since corrected for the *Journal.*

between both conductors and earth, i.e. the asymmetrical condition as described by the authors is assumed to exist. The method of entry into the receiver of this voltage is interesting and is not usually of the electromagnetic induction type but of a capacitive nature. Referring to Fig. A, the noise voltage V_1 is communicated to the chassis of the receiver by the various stray capacitances, together with a capacitance usually added with the intention of reducing mains noise; thus there now exists a second and somewhat smaller voltage V_2 between chassis and earth. If now the high-voltage end of the first tuned circuit has any small stray capacitance to earth, then a third voltage V_3 will appear by simple potentiometer effect across this tuned circuit, so producing a noise voltage which is amplified through the receiver and subsequently heard in the loud-speaker. If the stray capacitance from the high-voltage end of the first tuned circuit is made to chassis entirely, as opposed to earth, then no noise voltage will appear across the tuned circuit.

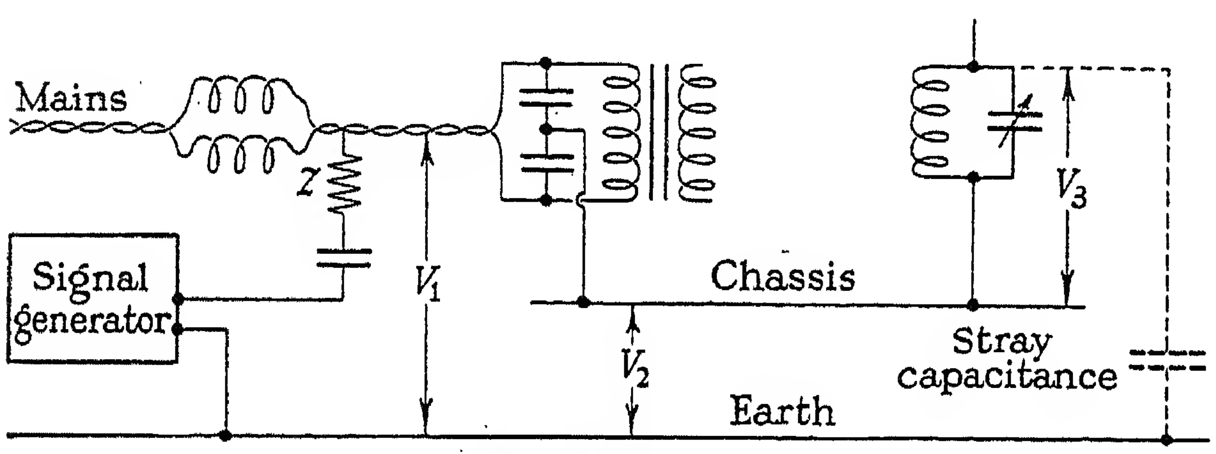

Fig. A

Various receivers were modified to fulfil this condition, and the following results were obtained: Receiver A, 30 db. improvement; Receiver B, 24 db. improvement; Receiver C, 40 db. improvement. In view of these results, we have tentatively instituted a new receiver measurement which we call the "sensitivity via the mains." It is rated as usual in microvolts for 50 mW audio-frequency output.

The method of measurement is, briefly, as follows: The signal generator is connected to the mains cord through an impedance (usually 100 ohms) simulating the source impedance of asymmetrical mains, and the input from the generator adjusted to give 50 mW audio-frequency output when the signal carrier is modulated 30 % at 400 cycles per sec.

Would it not be a useful inclusion to the usual standard receiver measurement, as recommended by the Radio Manufacturers' Association, if standardization on "sensitivity via the mains" were added?

Mr. A. J. Gill and Dr. S. Whitehead (*in reply*):

Degree of Protection.

As regards the degree of protection envisaged, raised by Messrs. Lee, Pawley, and Wynn, the following general considerations should be remembered. The C.I.S.P.R. have only considered so far the correction of non-earthed appliances. B.S.S. No. 800 applies to an item tested in the earthed condition if it can so be used. Accordingly the 500 μV corresponds to a limit of 200 μV or less for non-earthed appliances. Since the chance of an appliance being used in the earthed condition is at present only about 1 in 10 or 1 in 5, since manufacturers must suppress to a lower level in order to avoid rejections, particularly at the low-frequency end, and since a number of appliances are inherently non-interfering, it is clear that only a small proportion will have an interfering voltage as high as 500 μV.

Next there is the joint probability of such a machine being connected at the supply point which has the high coupling factor and of the receiver at the other end being simultaneously operated. It is very difficult to assess the final resultant probability, except to say that it must be very low. In a rough calculation made last year by one of us it was estimated that 96 % of listeners should be protected at present by a 500 μV limit with respect to a field of 1 mV/m., and substantially 100 % with respect to 10 mV/m.; but it is almost certain that the first estimate is pessimistic, and it is safe to say that the number of complaints should, although not eliminated, be very considerably reduced by the adoption of the present proposals.

It appears, from the analysis of certain test areas, that wireless licence-holders and electricity consumers are substantially the same people. To some extent therefore the remedy is in their own hands, and if, as seems likely, B.S.S. No. 800 is voluntarily adopted by most manufacturers, it should require comparatively little publicity to educate the public to require in their own interests the radio-interference-free mark. The Wireless Telegraph Bill now in preparation will no doubt provide some degree of compulsion, but the effectiveness of the measures will ultimately depend to some extent on the co-operation of the public with the manufacturers who are applying correction.

Domestic Appliances.

In connection with power-operated domestic appliances, mentioned by Messrs. Hill, Kinman, Lee, and Struthers, the majority of small motors do not exceed a rating of 500 watts. Vacuum cleaners and polishers are by far the most numerous and, with hair-dryers and fans, cover the great majority. The use of refrigerators is, however, developing, and it is usually found that interference due to the thermostat relay is more difficult to suppress, the motor following known principles.

The effect of the design of the appliance on the interference is complicated, although certain gross defects such as maladjustment of brushes, certain types of bad commutation, and fortuitous connection of parts, are known to increase the interference. A well-made motor should not vary greatly until its brushes are worn to the point of requiring replacement and/or adjustment for efficient running.

A manufacturer can only guarantee correction under the same terms as any other standard of quality, and it is therefore impracticable to envisage other than normal conditions of good usage. Apart from certain simple and avoidable causes of variation, the dispersion of mass-produced articles follows, according to recent tests, a more or less normal law, when the voltage is expressed in db. above 1 μV; and the standard deviation usually lies between 2 and 4. The number having a voltage 5–6 db. above the mean is usually less than 1 %. The high-frequency asymmetry of the machine has a considerable influence on the interfering voltage, and this asymmetry is difficult to reduce for a wide frequency band because it arises from distributed constants. Re-arrangement of

windings is sometimes useful, but is not easy to apply to multiple-speed machines. The iron-cored chokes recently developed show a considerable economy in size and weight and should not be a great inconvenience in those instances where the high-frequency impedance of the item is inherently so low as to render them necessary.

We agree with Mr. Colebrook that the term "mains attenuation" is likely to be misleading and we have amended it for the *Journal*.

Methods of Measurement.

We agree with Mr. Wynn that the tolerable signal-noise ratio must ultimately depend on the type of programme, but the listener also enters into the question and, in addition to the C.I.S.P.R. tests, subsequent tests lead to the result that the variation of the mean of a number of observers between different types of programme is less than the variation between different observers for the same type of programme. To obtain a complete solution would involve a lengthy and expensive study, as in the analogous case of telephone interference, but it is difficult to see what method of assessment is possible other than that adopted.

In answer to Mr. Strafford the approximate equality of electric and magnetic vectors has been shown for short-wave and ultra-short-wave interference; on the medium- and long-wave bands, a statistical connection has been made for trolley-buses between the radiation field at a distance and the indication of the standard measuring set at 10 yards. For lifts, attention has been drawn to the fact that the conception both of the interfering and of the broadcast fields inside a building is artificial. The distance of 10 yards was chosen largely for convenience in testing, and the indication is a standard of quality associated with the defined measuring set rather than an absolute measure. The resulting difficulty is mainly associated with the relative liability of receivers to interference, and the open aerial used in measurement is the more common in normal reception.

In reply to Mr. Keall, operation by $f(t)$ gives the instantaneous value of the resultant of the action of an intermittent conductor such as rectification is assumed to be; the load in the detector is assimilated in the filter network constituted by the low-frequency stages. The time-constant of the detector should, in so far as it may modify the audio-frequency response, be corrected by the later low-frequency stages if ideal rectification is to occur. The conditions of operation of the detector cannot differ greatly as between noise and signal, since these conditions are determined in both cases by the carrier, which is assumed to be large compared with either the noise or the modulation. The analysis does not apply to all those departures from ideal rectification, which can, nevertheless, give reasonable reproduction.

Miscellaneous Sources.

We are glad to hear from Mr. Bennett of the success with trolley-buses; trams, being obsolescent, are not always corrected. The error in Fig. 7, noted by Mr. Pawley, has now been corrected.

With reference to neon signs, if Mr. Strafford's objection is to the statement that current passes only during part of a cycle, this feature has been observed in actual oscillograms. While agreeing that relaxation oscillations can be stimulated in the way he describes, oscillograms have also shown, on occasion, damped trains of waves of the type associated with the spark excitation of a multiple resonant circuit.

In reply to Messrs. Forrest and Hill, new designs of insulator show distinct promise, and the types mentioned and others may prove advantageous both as regards normal use and also in avoiding interference. As may be seen from the values quoted, the field from overhead lines is such that interference should only be experienced in close proximity and may be expected to be rare, since such lines are mainly confined to the open country and avoid roads. The current transmitted has little effect on the interference. It is unlikely that interference is transmitted through a high-voltage transformer, although this is possible under some conditions. Distortion in the a.c. supply due to mercury-arc rectifiers is not really a radio problem. It is, nevertheless, very troublesome and difficult to remove. The best measures are to make the capacity of the system large compared with the rectifier load (load mixing), to augment the number of phases on the rectifier, to interpose as many transformers as possible between the rectifiers and the domestic supply, and, finally, to use filter networks, etc., which are often either inefficient or uneconomic.

Short-Wave Interference.

In reply to Mr. Megaw the oscillograms of the current in the automobile ignition discharge, now incorporated in the paper, agree more or less with the maximum observed in the field strength between 40 and 50 Mc., and also confirm his statement that the field strength decreases considerably for still higher frequencies. We appreciate with Mr. Watson the difficulties in the correction of motor cars, but there are a number of possible alternatives, such as to mount the coil on the engine or otherwise to provide a low-impedance path to the chassis, partial screening, resistors, inductors. It should be possible to find an economic solution in a given case, although much development work remains to be done.

Although ignition interference is more widespread, short-wave therapy constitutes the more troublesome problem, but is fortunately limited to certain centres and is intermittently operated. The allocation of certain wavelengths has not been officially proposed, but there is no doubt that a great amelioration of the position could, at least temporarily, be achieved. The medical profession is not, however, decided as to the frequencies which are required, and frequency indicators of sufficient accuracy might prove expensive. Screening can be made effective and portable screens are available abroad, but, even if the latter are satisfactory, treatment of a bed-ridden patient will still prove a difficulty.

The data given by Mr. Megaw are very interesting, and it may be mentioned that quite detailed rules have been drawn up in Canada to deal with electromedical appliances.

In reply to Captain McVicar, expanded metal is more efficient than netting, but the size of mesh cannot be greatly increased owing to the need for the elementary circuits to be of small linear dimensions. For a wide range of frequencies little advantage is to be anticipated

from double screening; it is usually more economic to employ the metal in a single continuous screen. Double screening can be disposed for optimum effect, but this depends in a complicated manner on the disposition, nature, and frequency of the radiating source. Window mesh can be bonded by a press joint to the frame and the whole sealed with cement; unfortunately, it is difficult and costly to pass it through a slot and to plumb or sweat. Well-galvanized metal has an indefinite life in dry plaster, but corrosion is likely in damp situations. Corrosion is much accelerated by stray currents, especially in concrete, so that circuits formed by dissimilar metals closed through the surrounding medium should be avoided.

Measures at Listeners' Premises.

In reply to Messrs. Kinman, Hill, Pawley, and Robin, a B.S. Specification for the sensitivity of receivers to interference, the means to reduce this, and the standards to be attained, is now in draft form. Section 3 of the paper gives a few general principles, but it was felt to be premature to deal with all aspects and the issue of the Specification must be awaited. The points raised will, we believe, be adequately treated therein, and the standard envisaged will make a not unreasonable distribution of the burdens as between the parties concerned. The trouble mentioned by Mr. Robin is related to incorrect or defective earthing. The Specification mentioned will contain directions as to earthing, a test of sensitivity to interference at the supply terminals, and a test of the efficiency of filters in reducing this.

Defective wiring is sometimes a cause of trouble, but the chief difficulty, high coupling factors, can occur with sound wiring. It has been decided that it is not economically possible to include the correction of ordinary lighting or power switches.

RESEARCHES IN RADIOTELEPHONY

By RALPH BOWN, M.E., Ph.D.

(LECTURE *delivered before the* WIRELESS SECTION, *4th May*, 1938.)

INTRODUCTION

Most of the technical problems which have been encountered in the development of radiotelephony over the past two decades have arisen in one way or another from the necessity of overcoming noise and distortion, two fundamental hazards to telephone transmission. Great research and development effort has been directed toward increasing the power of transmitters and sharpening the selectivity of receivers, simply because these are straightforward ways of reducing noise. In like manner the amplitude and frequency-response characteristics have been studied because perfecting them reduces distortion. In some applications of radiotelephony remarkable quietness and fidelity can now be secured. But in short-wave long-distance service there remain noise and distortion of serious proportions which have their genesis in the vagaries of the transmission medium itself and can best be mitigated by attack upon that part of the system.

One of the earliest weapons used in the attack on the medium was directivity—transmitting directivity to concentrate sending power, and receiving directivity to exclude circumjacent interference. Strangely enough, the newest and most potent weapon brought to bear is again directivity, still sharper directivity, but accurately controlled in accordance with a novel pattern built up by patient research.

DIRECTIVE ANTENNA RESEARCHES

Short-wave directive antennas had not long been in use before it was observed that the improvement they give must be viewed as a statistical average rather than as a fixed value. Occasions were noted when the gain of a directive antenna as compared with a simple doublet was much reduced; in the case of the sharpest receiving antennas the gain might even become negative, as though the antenna were not pointed in the right direction at all. This was taken as evidence of some sort of variability in the angle of approach of the signal, and as a warning that there were practical limits to the sharpening of directivity. Also it was found that the character of the fading and of the accompanying distortion might be different on different antennas; a further indication of idiosyncrasies in the directional behaviour of the signal.

That antenna directivity affected fading and distortion, and that multiple paths of different transit times might be involved, were remarked by C. S. Franklin in 1922 while describing before this Institution some early short-wave directive experiments of the Marconi Co. T. L. Eckersley had already presented proof that ionosphere reflections could explain night errors of radio direction-finding. A few years later Appleton and Barnett, and various other experimenters, settled beyond all doubt the reality of overhead reflections and of multiple, differentially delayed wave components. It also became better recognized that the ground, by reflecting downcoming sky-wave components back up into the antenna, modifies its theoretical "free space" vertical directive pattern, giving it, in the usual case, an upward tilt.

While it may thus be said that more than ten years ago the existence of a relation between antenna directivity, signal gain, and distortion, was generally understood, this understanding was of limited practical value and needed to be implemented by more specific information.

In a series of tests made in 1933 with the kind co-operation of the British Post Office, spurts or pulses of short-wave radiation sent out from Rugby, England, were received at Holmdel, New Jersey, U.S.A., on a simple form of directive antenna system capable of determining the angle, in the vertical plane, between the ground and the incoming ray. By displaying the received signal on a cathode-ray oscilloscope, the number and character of arriving pulses could be seen and recorded. Definite and useful facts were established as follows:—

(1) More than one pulse was usually received and the pulses came in at different times, that is they took different lengths of time to travel from their common source.

(2) The pulses came in at different angles to the earth.

(3) There was a correlation between the times and the angles; the longer the transit time the higher the angle of the trajectory.

(4) The conditions on the individual paths were fairly steady and not subject to fast variations.

These are the conditions which might be expected if the ideal picture of wave paths shown in Fig. 1(*a*) were actually to occur in nature. Fig. 1(*b*) shows how an ordinary simple directive antenna is broad enough in its vertical characteristic to receive several wave components at once. It is well known that the interaction of such wave components produces selective fading and the various forms of distortion resulting from it. Evidently any change in the antenna which modifies its directivity in the vertical plane would affect the nature of the selective fading.

To take advantage of the opportunities offered by this situation, a system known as a "musa" (multiple-unit steerable antenna) has been developed by Messrs. H. T. Friis and C. B. Feldman* and their associates at the Bell Telephone Laboratories. The principles of the experimental musa system in use at Holmdel, New Jersey, are shown schematically in Fig. 2, although many important apparatus details are omitted. Six horizontal

* See Reference (1).

rhombic antennas, arranged in a linear longitudinal array, are connected by coaxial lines to six phase-shifters whose outputs are combined. The phase-shifters are mechanically geared together in such a way that by turning a single control the sharp directivity given by the array may be aimed or steered at any desired vertical angle within the range of the unit antenna characteristics. As is suggested by the diagrams in Fig. 1, the array is so sharp that it may be steered to select one incoming signal ray from another and in this way to receive only signal components of about the same arrival time.

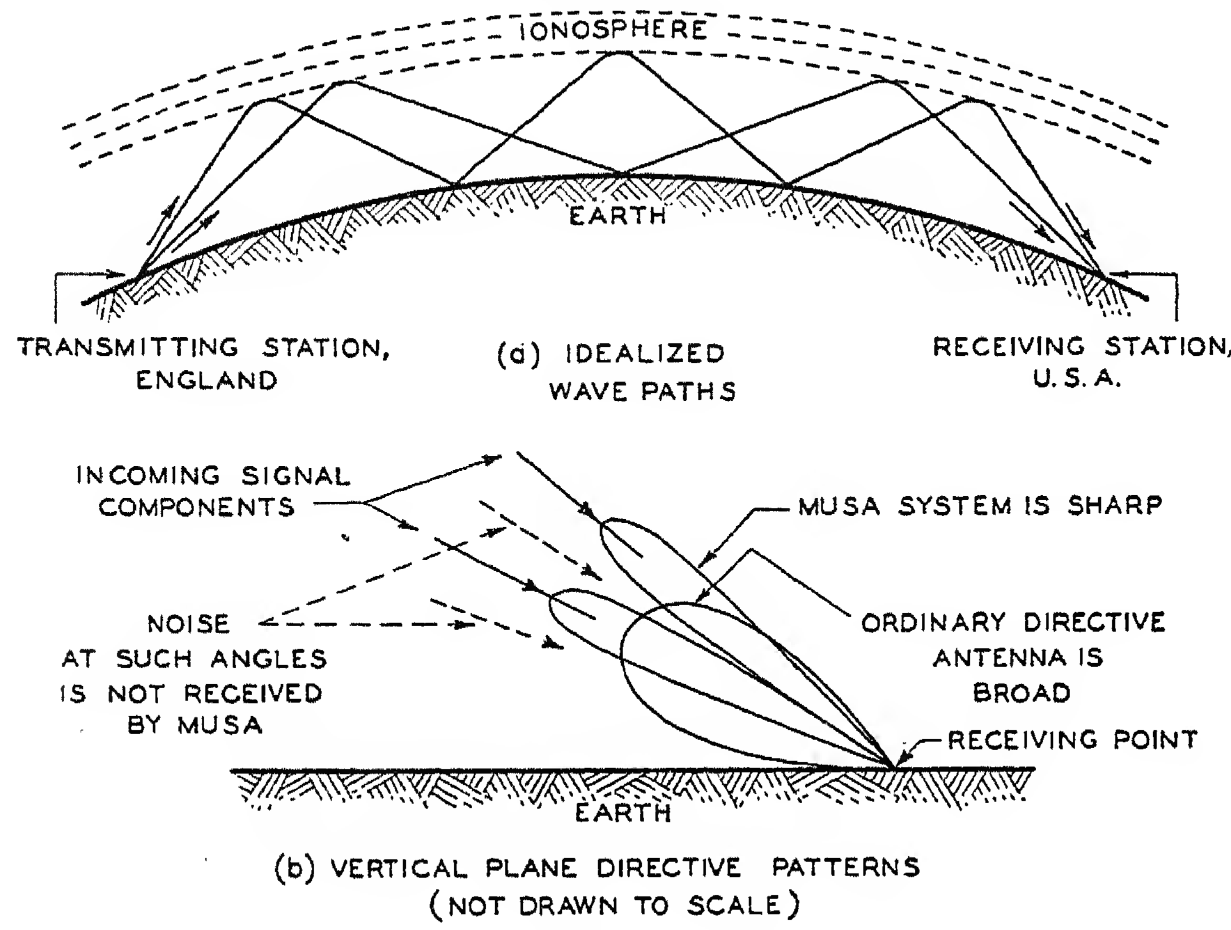

Fig. 1.—Physical basis for "musa" method.

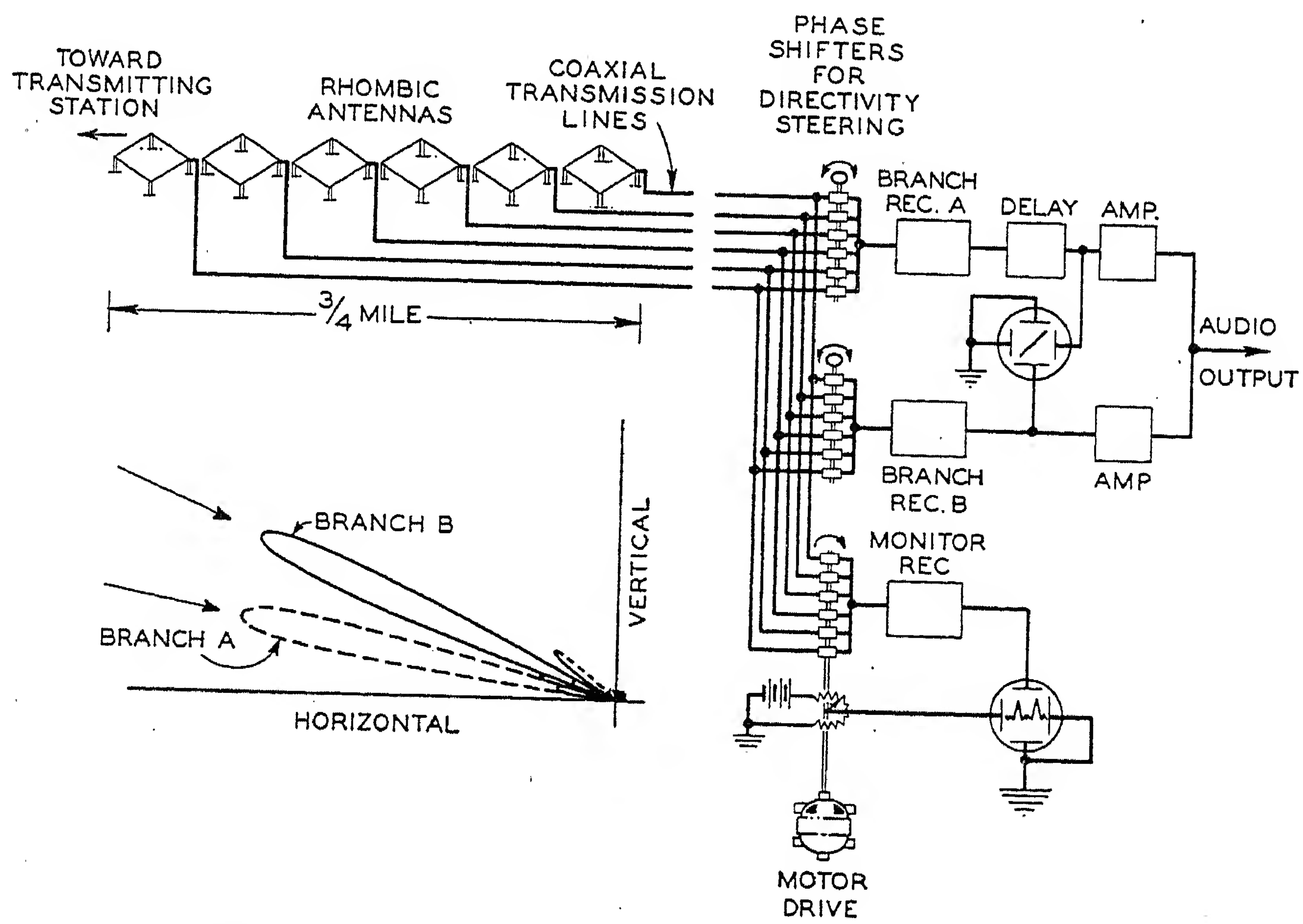

Fig. 2.—Simplified diagram of experimental "musa" system.

The antennas feed, in parallel, three separate phase-shifter groups, so that three independent outputs, steered for three different receiving angles, may be secured simultaneously. One of the phase-shifter groups is rotated continuously by a motor, to which is also attached a voltage-divider device for furnishing a linear horizontal-sweep voltage to a cathode-ray oscilloscope tube. The detected output of this branch of the receiving system is applied to the vertical deflector plates of the tube. The screen has a slowly decaying phosphorescence and exhibits, for each rotation of the phase-shifter gear, a curve of the relation between signal strength and angle to the earth in rectangular co-ordinates. In this way the angles at which the most effective rays are arriving can be observed, and the other two receiving branches may be set to receive any two desired rays.

The output from each such branch is found to be subject to considerable fading, but it is a much less selective fading than occurs with an ordinary directive antenna. For combining the outputs of the two branches, to gain the advantage of diversity, it has been found sufficient merely to introduce an audio-frequency delay into the branch receiving at the lower angle, to adjust the value of this delay until the two audio signals are in phase, and then to deliver them both to a common output. The delay adjustment is facilitated by a second cathode-ray oscilloscope which has the outputs of the two branches connected, respectively, to its two pairs of plates. Correct delay adjustment produces an inclined line on the screen, while for incorrect adjustment a maze of irregular circles and ellipses is seen.

Two definite improvements are given by musa receiving: (1) The sharp directivity of the receiving branches excludes noise not arriving at the same angles as the received signal components being selected; (2) the separation of the differentially delayed waves and the correction of delay before the components are permitted to combine, reduces selective fading and distortion. In the experimental system at Holmdel 7 to 8 db. improvement in signal-to-noise ratio is realized and the reduction in distortion is frequently quite marked.

CURRENT RESEARCHES IN DIRECTIVITY

With these favourable results from employing sharp steerable directivity at the receiver, it is natural to reason that similar control of directivity at the transmitting end might be beneficial. To explore this possibility a series of transmissions is being sent from Deal, New Jersey, using a simple array of two antennas whose vertical directivity is varied cyclically so as to sweep a null point in the polar radiation diagram repeatedly through a range of vertical angles. Engineers of the British Post Office are co-operating by receiving and recording these signals. Not enough data have been analysed to justify any conclusions but there is found, as one might expect, a suggestion that these east-bound signals follow paths related to the west-bound signal paths which are contemporaneously observed by means of the musa receiver at Holmdel.

While the experiments with the "musa" receiving system have been most gratifying, it has been true that at times the conditions existing seemed to be far from those shown in the ideal diagram of Fig. 1, and the system was unable to cope with them satisfactorily. The evidence, both from the musa tests and from reports of other experimenters, gave ground for suspicion that the difficulty lay, not in unusual behaviour of the wave paths in the vertical plane, but in anomalous performance in the horizontal. At times of severe and very fast fading (flutter fading) observations with simple direction-finding equipment indicated a shower of wave components scattered through a considerable range of angles around the great-circle direction to the transmitter. Following this lead, directional studies are now being pushed into the horizontal dimension, and striking data are being secured with a musa system comprising a broadside array of receiving antennas arranged for sharp steerable directivity in the horizontal plane.

In this work we have not only observed the trans-atlantic telephone transmissions from the Rugby station of the British Post Office, but also have found a special advantage in the transmissions of the British Broadcasting Corporation from Daventry, because of the variety of transmitting directivity used. Frequently there is simultaneous sending of the same programme in different directions, on different antennas, but on the same frequency. The B.B.C. have been most kind in giving advance information on schedules, antennas, etc. For a comprehensive discussion of this horizontal directivity study I must refer to a recent letter to *Nature* and to a forthcoming paper in the *Proceedings of the Institute of Radio Engineers*, both by Mr. C. B. Feldman.* I would like to mention, however, a few examples of the kinds of conditions which have been observed.

When the path between England and the United States is entirely in daylight, the transmission along the great-circle route is always predominant. This seems to be as true during the abnormal ionosphere conditions

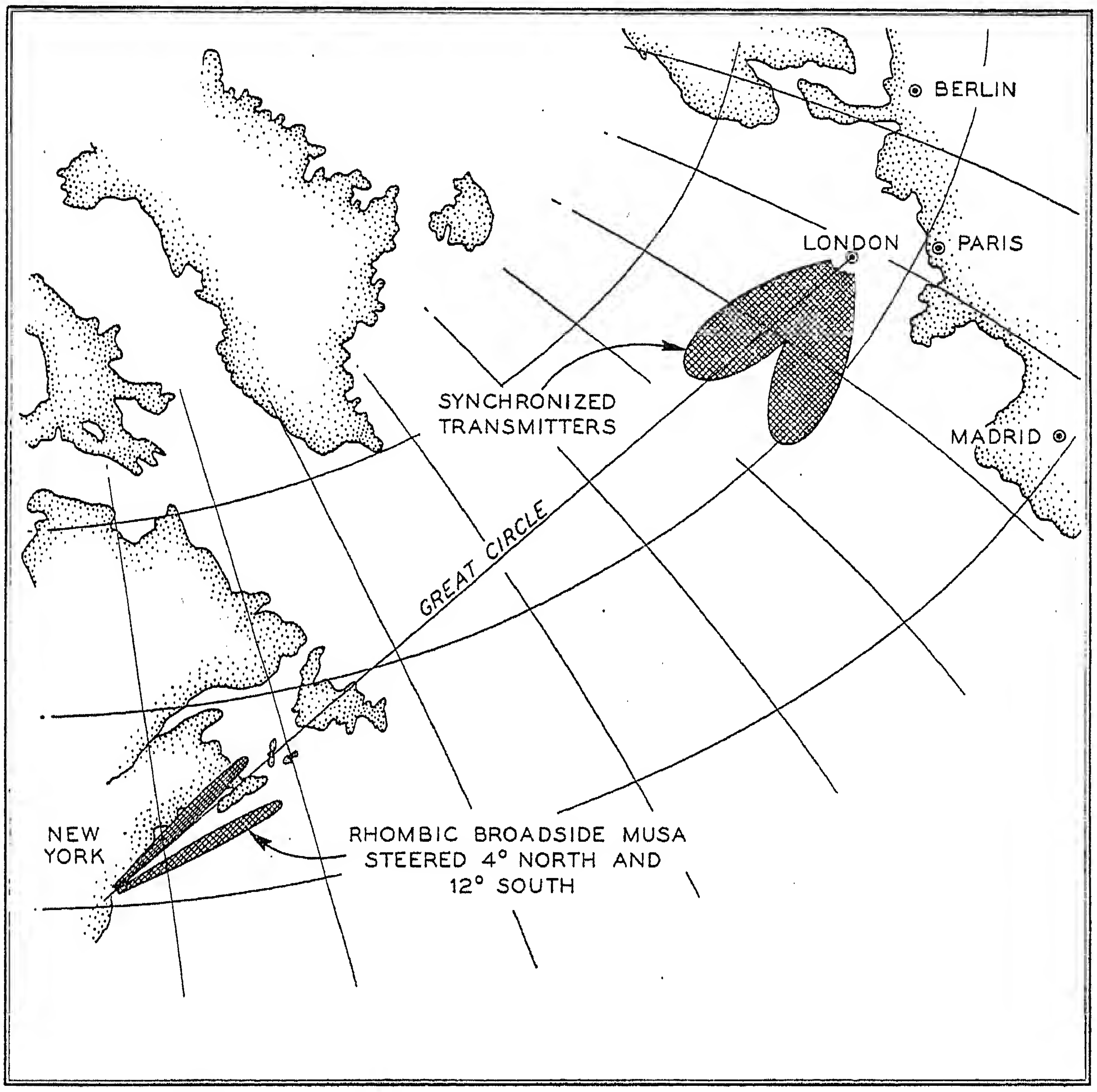

Fig. 3.—Diagram of conditions experienced on the 23rd November, 1937.

* See Reference (2).

associated with solar disturbances as it is in normal times.

When there is darkness, or partial darkness, on the intervening space, the great-circle route no longer provides the sole transmission path. Frequently there are also waves arriving at other azimuths.

In a considerable number of instances it has appeared as though the ionosphere were warped, there being definite shifts of the direction of wave arrival, sometimes to the north and sometimes to the south, with little regard to the transmitting directivity.

In magnetically disturbed evening periods great-circle paths appear to be attenuated so much that more southern routes often seem to provide the principal means of transmission, even in the case of transmissions directed sharply at New York.

On the afternoon of the 23rd November, 1937, during a moderate ionosphere disturbance, occurred the peculiar circumstances illustrated by Fig. 3. Transmission 4B from Daventry employed two synchronized transmitters, radiating from separate antennas, on 11 750 kc./sec. One was directed at 6° north and the other at 28° south of the true direction to New York. At Holmdel two distinct incoming wave paths were observed, one 4° north and the other 12° south of the great-circle direction to Daventry. Using the broadside musa system these could be separately received. There was a transmission time differential of 1·4 milliseconds between the two paths, the southerly path being longer by this amount.

Much greater deviations have been noticed. For example, at one time during disturbed conditions on the 28th May, 1937, the strongest and steadiest component was 50° to the south of the great circle. A somewhat weaker 5° northerly path also existed.

Although southern paths are usual, they are not always predominant. In the severe magnetic disturbance of 16th–25th January, 1938, marked southern deviations occurred as the magnetic storm developed, and as it receded, but for the period of its greatest intensity a somewhat northerly path was much the most prominent.

Many observations of this sort have been made, and theories to explain them have been formulated, but it is too early to draw practical conclusions. There must be admitted, however, a strong implication that wide-range azimuthal steering of both transmitting and receiving antennas holds promise of improving transatlantic circuits during afternoon and evening hours, particularly when the ionosphere is abnormally disturbed.

SPEECH-CONTROLLED DEVICES

Turning now from directivity to a still older principle for reducing noise interference, I wish again to discuss some recent developments.

The oldest and most direct method of improving signal-to-noise ratio is to boost the signal by increasing transmitter power capacity. When the capacity has been raised to a technical or economic limit, the ingenuity of the engineer is taxed to devise other ways of still further increasing speech power output. One of the most effective of these methods, single-sideband transmission, I shall deal with later. For the moment I wish to consider methods which modify the amplitude characteristics of the speech signal at voice frequencies. Time will permit only a superficial and merely illustrative excursion into this subject.*

Even when there is little inflection in speech, the maximum voltages from a microphone may be as much as 30 db. (30 times amplitude) higher than the significant voltages generated by the weakest sounds. Among different combinations of talkers and connecting lines there may be an additional range of variation of over 40 db. Thus, in commercial systems, a spread of something like 70 db. may actually be encountered between the weakest and the strongest currents it is desired to transmit satisfactorily. The usual way of ironing out the worst of these variations is through manual control of gain by a monitoring operator. The louder conversations or passages of a conversation are depressed, to avoid overloading, and the weaker ones are raised to override the noise. Although it makes a large first-order improvement, this method is obviously incomplete and has all the uncertainties introduced by the human element. The first important improvement to go into commercial radio telephone use was the "compandor," which has operated successfully for some years on the New York–London long-wave circuit.

The compandor does not attempt to substitute for the operator in adjusting the general level of speech; it performs a quite different function which the operator cannot possibly do. The compandor comprises two pieces of apparatus—a compressor at the transmitting end and an expandor at the receiving end of the radio channel. The compressor is a voice amplifier with a fast-acting automatic gain control, which smooths out the speech syllable by syllable and reduces or "compresses" to one half (as measured in decibels) the range of amplitude variation of signals passing through. If the signal thus compressed is used fully to load a radio transmitter, the average volume, and in particular the weakest parts of the signal, will be transmitted at higher level than if no compression had been applied. The weaker sounds in this way override noise more satisfactorily.

At the receiving end the expandor has a sort of *negative* automatic volume control action which doubles (in decibels) the range of variation of signals passing through it. It undoes the work done by the compressor, and expands the speech signal to its original volume range. The net result is an improvement in average signal-to-noise ratio, with no net change in the nature of the signal.

Since the action of the expandor is controlled by the variations of received speech signal itself rather than by a separate pilot channel, spurious changes in intensity caused by fading cannot be distinguished from real signal characteristics and are also exaggerated or "expanded." For this reason the compandor has not been applied to short-wave circuits. A compressor alone is of some value but has not been commercially applied. The expandor, used alone at the receiving end, has a certain beneficial effect, and there has been developed a limited range expandor, sometimes called a "noise reducer," which is better adapted to produce this effect.

The noise-reducer is representative of a class of devices employing a marginal or threshold characteristic. Three different adjustments available in one model of noise-reducer are illustrated by the three curves of Fig. 4. At

* See Reference (3.

small values of input, that is for small amounts of noise appearing in the otherwise silent intervals between words or sentences, the gain, and consequently the output, is low. Inputs of higher value cause the gain to rise more or less abruptly to normal value, and full output on actual signals is secured. It is inevitable that some of the weakest parts of the speech will fail to actuate the gain-increasing function and will be lost. If the marginal operating point of the control circuit is correctly adjusted a little above the prevailing noise level, the speech which fails to actuate the control will be so near the noise level as to be of small value in any event.

While the operation is clearly one of separating the received signals and noise on an amplitude basis, it should be carefully noted that no discrimination is ever achieved between signals and noise which occur simultaneously. The action is simply to suppress both the noise and those speech sounds which are submerged in it. The noise-reducer is at a disadvantage when placed on the output

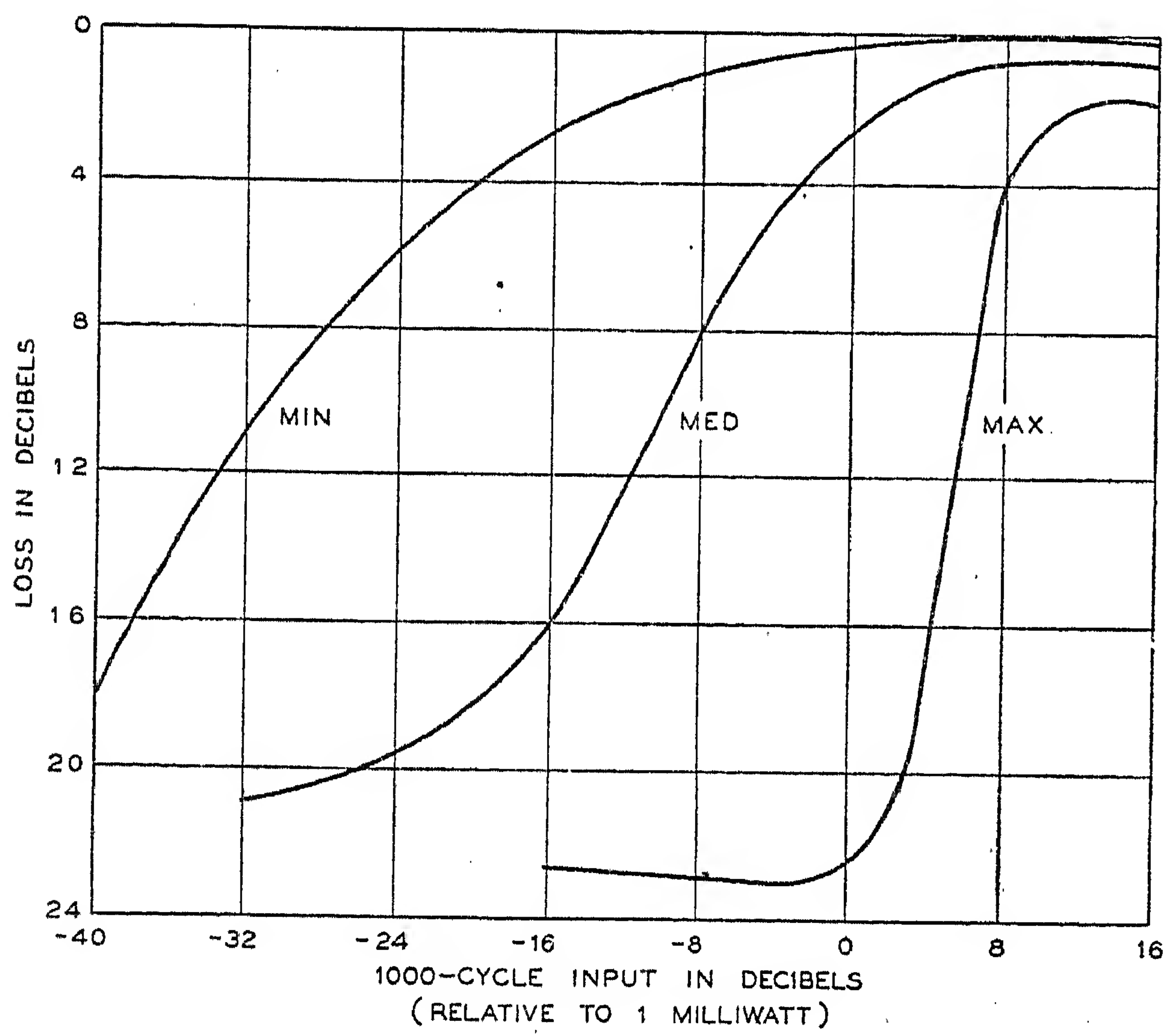

Fig. 4.—Performance curves of a noise-reducer for three different adjustments.

of a circuit subject to fading, because the best margin setting then is not a fixed value but differs from moment to moment; hence a compromise adjustment must be used.

Smoothing out volume variations is a problem upon which important progress is being made. We now have volume-limiters which prevent excessive amplitudes without the distortion caused by the old-fashioned peak-chopper or amplitude-limiter. A volume-limiter has a fixed gain and a linear relation between input and output as long as a selected limiting value of volume is not exceeded. For inputs beyond this limit the gain of the device automatically drops rapidly enough to prevent more than a momentary transient increase of output. The characteristic is again linear at the reduced gain. The gain returns gradually to normal after the excessive input has ceased. The oscillograms in Fig. 5 show how a particular volume-limiter reacts when the input is suddenly increased 10 db. above the limiting value.

In America, volume-limiters of appropriate characteristics are being employed commercially in diverse fields; in radio broadcast transmitter input control, to prevent overloading and permit increasing average programme level; in multiplex wire carrier telephony, to reduce interchannel interference by limiting speech peaks on the individual channel inputs; in short-wave transatlantic single-sideband circuits, to supplement receiver automatic gain control in reducing volume variations.

The volume-limiter curbs excessive upward variations in volume, but as ordinarily used has no effect upon undesirably low volumes. One kind of device which accomplishes both these things has been called a "vogad," a synthetic name derived from the words "voice-operated gain-adjusting device." It attempts to do all that a monitoring operator can do by his listening and by his adjustment of a gain control, and in addition has a certain amount of volume-limiter action. It has two interlocked control circuits. One samples the input speech, and if the volume is low it operates to raise the gain. The other control samples the output speech, and if the volume is up to the desired level it operates to disable the operation of the first control circuit. If the output volume is already above the desired level the second control circuit acts further to decrease the gain. In the case of sudden loud sounds the volume-limiter feature becomes effective until the slower controls can come into action. Except

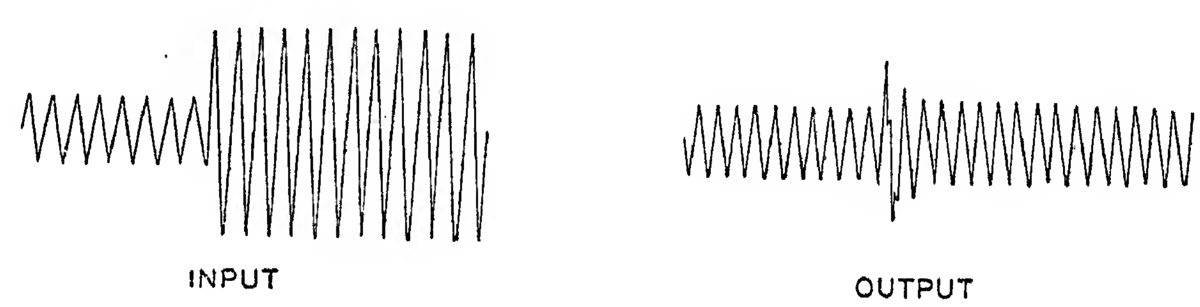

Fig. 5.—Oscillograms showing action of a volume-limiter.

for this volume-limiter function a vogad does not "compress" the speech, that is, it makes substantially no alteration in the moment-to-moment ratios between maximum, minimum, and average voltages of the speech signals. It simply readjusts the gain setting, when needed, to compensate for changes of input volume,* and thus maintain a practically constant output volume. It has the important feature that its gain does not change during pauses in the conversation. The gain remains where it was left by the last words passed, and awaits a recommencement of the talking.

Tests of vogads as against human control on transatlantic circuit operation have shown favourable results. In a ship-shore radiotelephone station under construction at Norfolk, Virginia, a vogad will be employed experimentally to take over the job of regulating volumes into the radio transmitter.

SINGLE-SIDEBAND TRANSMISSION

Single-sideband transmission offers a way of reducing noise and distortion in short-wave telephony which is destined to be of increasing importance.

The single-sideband method, invented in 1915 by John R. Carson, was used in 1917 in wire carrier systems, then considered "high frequency" although the highest band was less than 50 kc./sec. Its application to radio came

* Volume as defined by the well-known class of visual-reading meter devices called "volume indicators."

10 years later, in the first commercial transoceanic circuit between New York and London. This circuit operates at about 60 kc./sec. and, like the wire systems, employs single sideband with complete suppression of the carrier.

There are two well-known advantages in this method of transmission as compared with ordinary modulated carrier or double-sideband transmission. The first, which is a matter of amplitudes, is that the output of effective signalling power from the transmitting system can be multiplied by four (raised 6 db.) if the carrier is dropped out and all the power of the amplifier is put into the sidebands. The second advantage has to do with band width. By eliminating one sideband and concentrating all the power in the remaining sideband, the occupied band is cut in half and the signalling power per kilocycle is doubled. Assuming that noise is uniformly distributed in frequency and that the receiver is selective enough to exclude all noise except that lying directly in the single sideband intermixed with the signal, an improvement of 3 db. is secured. This makes a total net improvement of 9 db. in signal-to-noise ratio—6 db. at the transmitter and 3 db. at the receiver.

Theoretical analysis of the virtues single-sideband transmission might have where selective fading is present, and experimental testing of its performance on a transatlantic short-wave circuit, were carried out about 10 years ago, but it was not until more recently that complete systems suitable for commercial use were brought forward. In reporting the early experiments it was concluded that single-sideband suppressed-carrier transmission gave less distortion. The conclusion was explained as being due to the fact that a locally supplied carrier was always present in the receiving detector, and it was impossible to have the "blasting" which occurs in double-sideband transmission when the carrier fades out and the sidebands alone remain. Practical operation has now amply demonstrated the reality, not only of the 9-db. gain in signal-to-noise ratio, but also of the improvement in distortion, and the value of the single-sideband system for short-wave telephony seems clearly established.

The first commercial application was to the Netherlands–Java circuit. The Dutch engineers, not content with this achievement, have advanced their work rapidly into the field of multiple channel transmission.

Single-sideband systems have been put into operation between New York and London, and between San Francisco and Honolulu.

There is some divergence of method in handling the carrier frequency. In the Netherlands–Java system, as described in the literature,* the carrier is suppressed and a pilot channel is transmitted at some distance off the upper edge of the speech band, 5 kc. from the carrier position. The system adopted by the American Telephone and Telegraph Co.,† the British Post Office, and others, transmits the carrier in reduced amount, 10 to 20 db. down from normal strength. At the receiver the carrier is separated out and, after being amplified and smoothed or "reconditioned," either is itself fed to the detector or is used to synchronize a local oscillator which in turn supplies the carrier voltage needed in the process of detecting the sideband.

In experimenting with such receiving systems a curious effect has been noted. The carrier is separated from the sideband by passing it through a narrow crystal filter about 40 cycles wide. If, instead of a carrier, a sufficient amount of valve noise or resistance noise is impressed on the input of the filter, its output is still capable of demodulating the speech sideband with little loss of intelligibility, although the detected speech has a peculiar gurgling quality. The resistance-noise impulses have been drawn out by the filter into long transient oscillations of carrier frequency. As might be expected, the gurgling becomes slower if the filter is narrowed still further.

* See Reference (4).

† *Ibid.*, (5).

MULTI-CHANNEL PROBLEMS

To secure more efficient use of frequency space in the radio spectrum, it is desirable to progress in the direction of close-packed, grouped channels. In wire and coaxial systems large numbers of telephone channels are sent in a single group, on the scale of 4 kc. per telephone channel. Why can we not do this easily in radio?

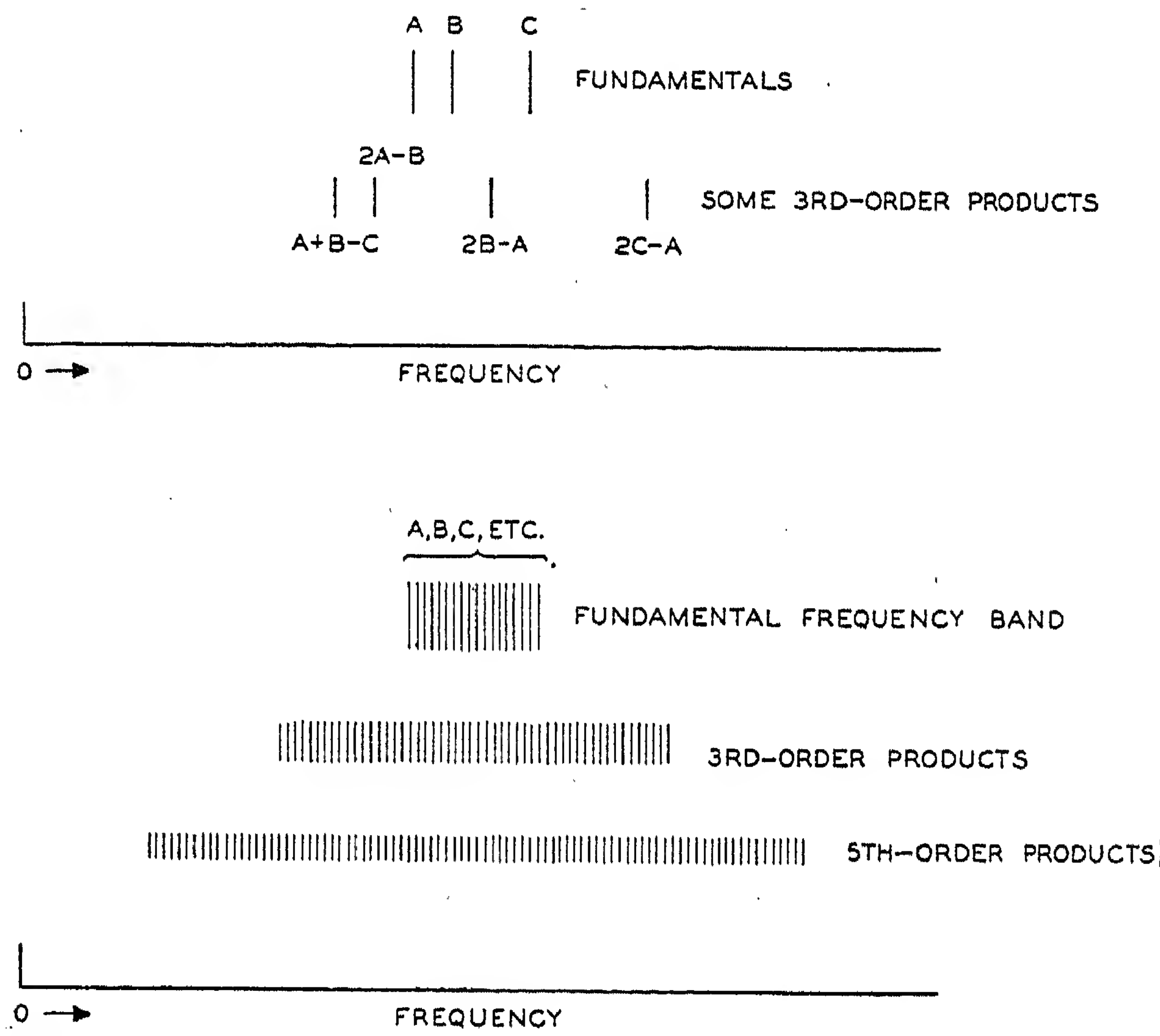

Fig. 6.—Diagram to illustrate odd-order modulation products.

Experiments confirm the expectation that one of the major difficulties is intermodulation between the channels. Theoretical analysis of intermodulation is by no means an easy or straightforward subject. There are, however, a few simple concepts so helpful in visualizing the nature of the problem that their lack of rigour may be overlooked for present purposes.

Objectionable modulation products are caused mainly by distortion in the high-power amplifier stages of the radio transmitter. Such of these products as are well removed in frequency from the signalling bands are of little concern, since they may be adequately suppressed by shielding and by selective output circuits. The so-called odd-order products (3rd, 5th, 7th, etc.) which fall into or close to the fundamental frequency bands, are the seriously disturbing element.

The nature of these products is illustrated in a crude way by Fig. 6. Consider three individual frequencies A, B, and C, representing three components arbitrarily

selected from a band of signal frequencies to be transmitted. They are marked "Fundamentals." Intermodulation between them produces new frequencies of the kind A + B − C, A + A − B, 2C − A, etc., in which all combinations and permutations of a sum and difference of any three elements may occur. A few of these are shown in the figure, marked "Some 3rd-order products." Note that they fall both near and among the fundamentals. Now let A, B, and C, be generalized, i.e. moved about so as to represent at one time or another any and all of the frequencies in a signal band to be transmitted. This is illustrated by the lower part of Fig. 6. Evidently intermodulation among a band of fundamentals generates a band of 3rd-order products of three times the width.

Three fundamental elements combine to produce one of those spurious frequency elements which we call a 3rd-order product. In a similar way combinations and permutations of 5 fundamental elements can produce spurious frequencies of the 5th order (for example, A + B + C − D − E, or 2A + B − 2C, etc.) covering a band 5 times the width of the fundamental. In general, the higher orders become rapidly weaker. In many cases only the 3rd order is of material importance.

It is interesting to examine the significance of these odd-order modulation products in the problem of conserving radio-frequency space by single-sideband methods.

Consider first the nature of double-sideband transmission as shown in Fig. 7(*a*). Only 3rd-order products are indicated. Spurious frequencies, into the formation of which the powerful carrier frequency enters as a component element, are of greater magnitude than the others. In the diagram 3rd-order products which can be of this kind are indicated by longer vertical lines.*

If one sideband is eliminated and the carrier is reduced and the remaining sideband is increased, the condition changes to that shown in Fig. 7(*b*). The band occupied by the fundamental frequencies becomes narrower in the ratio of 2 : 1, and that occupied by the 3rd-order products also contracts 2 : 1.

Experimental measurement of distortion products on an actual transmitter checks fairly well with this simple analysis, as may be seen from Fig. 7(*c*). Here are plotted the distortion products picked up by a sharply selective single-sideband receiver when tuned with its mid-band frequency displaced from the carrier position by different amounts. One curve is for ordinary double-sideband transmission; the other is for single-sideband reduced carrier transmission. In both cases the modulating speech was inverted. The same peak load on the high power amplifier was used for both kinds of transmission. The ordinates are in decibels referred to the single-side band signal correctly tuned in. By their wide spread these curves indicate that 5th-order, and possibly even higher-order, products are present in measurable magnitude.

It is customary to establish the adjustment and loading of transmitters to meet limits of signal distortion which do not curtail intelligibility and do not offend the ear. Study of experimental evidence shows that something more than this is necessary to permit packing radio channels as closely as channels are packed in wire circuits. The modulation products which fall back into the band occupied by the fundamental frequencies become inextricably mixed with the signal and are recognized at the final output as signal distortion. The fringe products, which fall outside the fundamental band, may spread into neighbouring channels of communication if these lie close enough. Products falling back into their originating channel as signal distortion may be tolerated up to a magnitude of perhaps 5 % of the fundamental (25 db. down); for products which appear as cross-talk in another telephone channel a value of less than 1 % of the signal in that channel is desirable (more than 40 db. down).

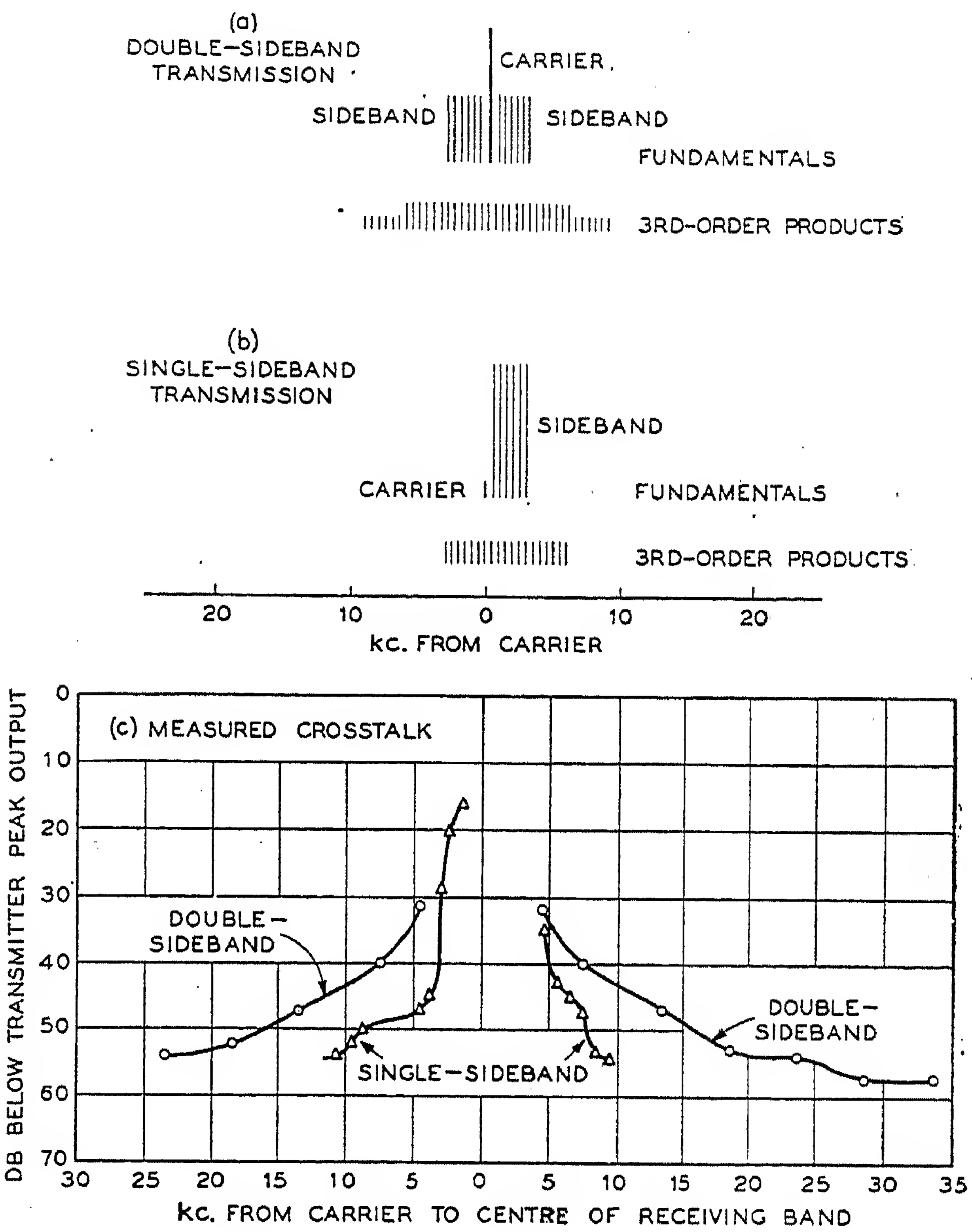

Fig. 7.—Comparison of double-sideband and single-sideband modulation products.

Assuming a tolerable cross-talk ratio of 40 to 45 db., it might appear, from the single-sideband curve of Fig. 7(*c*), that channels of equal powers could be spaced 5 or 6 kc. between centres. The conclusion is justified only if it is certain that the modulation products from one channel (channel "x") which fall into any other channel (channel "y") have fading variations equal to and contemporaneous with those experienced by the fundamental components of channel "y." This condition can be produced with certainty only by radiating channel "y" and the modulation products of channel "x" both from the same antenna so that they will follow identical transmission paths. If they are radiated from separate antennas, or from different stations, channel "y" may fade down

* The diagrams (*a*) and (*b*) illustrate band widths primarily and are not intended to be more than crudely suggestive of relative amplitudes.

when the modulation products from channel "x" fade up, and the cross-talk ratio may, for a considerable part of the time, be intolerable.

The method at present most available for introducing several closely spaced channels at higher power into a common antenna is to aggregate the channels into a group at low power and then to amplify them in a common power amplifier which feeds the antenna. In the amplifier not only does each channel generate its own modulation products as pointed out above, but additional products are generated by intermodulation between the different channels, and the cross-talk and interference problems become much more complicated.

In wire systems handling many channels in a group, the amplifier valves can be operated with large amounts of negative feedback to reduce intermodulation to very small values. Whether it will be possible to obtain satisfactory efficiency and freedom from distortion in high-power radio-frequency amplifiers will depend not only upon problems imposed by the greater magnitude of power and frequency, but also upon the adaptability of the necessary circuits to practical operating requirements, such as quick and easy wave-changing.

Presumably the goal will not be achieved in one stroke, but will be approached by various practical compromise schemes which make good use of the available art. The 2- and 3-channel arrangements tried out on the Netherlands–Java circuit, and the twin-channel system being tested between New York and London, are examples of progress along this line. At any rate we may be sure that research workers will continue to do their part toward making it more difficult to be pessimistic about the limitations of radio-frequency space.

REFERENCES

(1) H. T. Friis and C. B. Feldman: "A Multiple-Unit Steerable Antenna for Short-Wave Reception," *Proceedings of the Institute of Radio Engineers*, 1937, vol. 25, p. 841.

(2) C. B. Feldman: "Deviations of Short Radio Waves from the London–New York Great-Circle Path," *Nature*, 1938, vol. 141, p. 510.

(Mr. Feldman presented at the Annual Convention of the Institute of Radio Engineers at New York, 18th June, 1938, a paper having the same title as the above letter to *Nature*. This paper is expected to be published in due course in the *Proceedings of the Institute of Radio Engineers*.)

(3) A. C. Norwine: "Devices for controlling Amplitude Characteristics of Telephonic Signals."

(This paper, which is a comprehensive survey of the subject with an extended bibliography, was presented at the Pacific Coast Convention of the American Institute of Electrical Engineers at Portland, Oregon, 11th August, 1938, and is expected to be published in due course in the *Bell System Technical Journal*.)

(4) N. Koomans: "Single-Sideband Telephony applied to the Radio Link between the Netherlands and the Netherlands East Indies," *Proceedings of the Institute of Radio Engineers*, 1938, vol. 26, p. 182.

(5) A. A. Oswald.: "A Short-Wave Single-Sideband Radiotelephone System."

(This paper was presented at the Annual Convention of the Institute of Radio Engineers at New York, 16th June, 1938, and is to be published in due course in the *Proceedings of the Institute of Radio Engineers*.)

THE APPLICATION OF TRANSMISSION-LINE THEORY TO CLOSED AERIALS*

By F. M. COLEBROOK, B.Sc.

[From the National Physical Laboratory.]

(*Paper first received* 22*nd December*, 1937, *and in final form* 26*th February*, 1938.)

SUMMARY

The paper contains an analysis of the behaviour of frame aerials consisting of a single turn of conductor. It is assumed that the behaviour of such systems, including the mutual interactions of the various elements, can, to a useful degree of approximation, be represented by the differential equations of classical transmission-line theory. Formulae are obtained for the effective induced e.m.f. and the effective impedance (at the tuning point) of frame aerials the dimensions of which are not small compared with the wavelength, both for symmetrical and asymmetrical systems of tuning. It is found that in the case of symmetrically tuned systems the output voltages across the two equal halves of the tuning impedance will not in general be quite equal.

It is shown that the "resonance factor" of a frame aerial (i.e. the ratio of output voltage to induced e.m.f.) can be determined by the usual method of reactance-variation at a constant frequency, in spite of the non-uniformity of the current distribution along the length of the conductor, but that the same process carried out by variation of frequency will not, in general, be valid.

It is shown that for a given total length of conductor the optimum shape of a rectangular frame aerial, with respect to induced e.m.f., is square. In particular, a square frame with side equal to half a wavelength appears to have useful practical characteristics in respect of sensitivity and symmetry, both for field-strength measurement and direction-finding.

The method of applying the formulae to circular loops by a process of integration is given and illustrated by particular cases. It is found that in the case of small closed aerials the magnitude of the induced e.m.f. is not very sensitive to shape.

CONTENTS

CONTENTS—*continued*

(1) OBJECT AND SCOPE

The most important uses of closed-coil or "frame" aerials are (*a*) directional reception and (*b*) field-strength measurement. The present paper has some bearing on the first of these, but is chiefly concerned with the second. In this application the e.m.f. induced in a closed aerial of total area turns A, located with its plane perpendicular to the wave-front of a linearly polarized electric wave of intensity e, is assumed to be given by

$$E = \frac{2\pi}{\lambda} Ae \quad . \quad . \quad . \quad . \quad . \quad (1.1)$$

Further, if the closed aerial have total inductance L_a and total effective resistance R_a, the potential difference V produced across the tuning condenser is given by

$$V = \frac{\omega L_a}{R_a} E \quad . \quad . \quad . \quad . \quad . \quad (1.2)$$

$$= \frac{\omega L_a}{R_a} \cdot \frac{2\pi}{\lambda} Ae \quad . \quad . \quad . \quad . \quad (1.3)$$

Thus, to borrow a term which has come into use in direction-finding, the "pick-up factor" of the closed aerial is

$$\frac{V}{e} = \frac{\omega L_a}{R_a} \cdot \frac{2\pi A}{\lambda} \quad . \quad . \quad . \quad . \quad (1.4)$$

consisting of two terms, a "resonance factor" and an effective e.m.f. factor.

The above simple formulations are based on the assumption that the total length of the conductor and all other dimensions of the closed aerial are so small compared with the wavelength that the current distribution is substantially uniform along the length of the conductor.

In many practical cases, particularly in the measurement of field strength in the metre band of wavelengths,

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the limitations of physical size involved in these assumptions are inconvenient. The principal object of the present paper is to arrive at formulae corresponding to those given for V and E above, which shall be valid for cases in which the current distribution cannot be assumed to be uniform, or the linear dimensions small compared with the wavelength. A secondary object was to examine the possibilities of certain special sizes and shapes of single-turn closed aerials, i.e. cases in which the principal dimensions are simply related to the wavelength of operation.

The present paper is purely analytical in character. Experimental work on the subject is in progress, and it is hoped to publish some account of this in the near future. Meanwhile, however, it has been thought desirable to publish the present theoretical discussion, since field-strength measurement, particularly at short wavelengths, is a subject of growing importance which is already being studied by a number of different groups of workers. The formulae developed in the analysis may be of some guidance in the interpretation of existing and accumulating experimental data. These data, on the other hand, may throw some light on the validity of the assumptions on which the analysis is based. Thus the theoretical conclusions are put forward in this tentative sense, both as furnishing suggestion for experimental work and as material for criticism in the light of practical experience.

(2) THE METHOD OF ANALYSIS AND THE ASSUMPTIONS INVOLVED

In a previous paper* it has been shown that the application of the classical transmission-line theory to open earthed aerials leads to theoretical conclusions which are, to a practically useful degree, in accordance with the actual behaviour of such aerials. Essentially, the physical assumption involved is that the linear conductor constituting the aerial can be regarded as having, at any given frequency, a uniformly distributed resistance, inductance, and capacitance, per unit length.

It might be thought that the existence of radiation resistance in aerials would invalidate such an assumption from the outset, but this is not necessarily the case. In fact, Brainerd has shown that† radiation resistance, or "radiactance" as he prefers to call it, can be represented as an addition, to the ohmic resistance per unit length, of a term consisting of a constant multiplied by the square of the frequency. The proposed formulation may therefore be valid at any given frequency, inclusive of radiation resistance.

Again, there will undoubtedly be some reaction of one part of a closed aerial on the remainder, but even this will not necessarily invalidate the proposed formulation, since such reaction may conceivably be represented for the most part by an effect on the magnitude of the assumed constants rather than a change of the form of the differential equations. Some such explanation must exist for the satisfactory agreement already mentioned between theory so based and experimental observation in the case of the open earthed aerial.

Thus there are good reasons for trying out the proposed formulation in the case of closed aerials, at least in the case of closed aerials consisting of a single turn, such as are generally used at short wavelengths. The formulae so obtained are likely to be somewhat more accurate than those which do not take into account the non-uniformity of the current distribution.

* See Reference (1).

† *Ibid.*, (2).

(3) THE BASIC SYSTEM CONSIDERED

The basic subject of analysis is illustrated in Fig. 1 (the closed loop of conductor is shown as circular in shape but is not necessarily assumed to be so in fact). The length of the conductor (l) is considered as divided into three parts l_1, l_2, and l_3, in the second of which a uniform e.m.f. e per unit length is induced by the field. All the practical cases involved can be derived as special cases or combinations of such systems.

As usual in single transmission-line theory, the potentials along the conductor are relative to earth as zero. For generality, two tuning impedances are shown, connected in series. They may in practice be equal, as

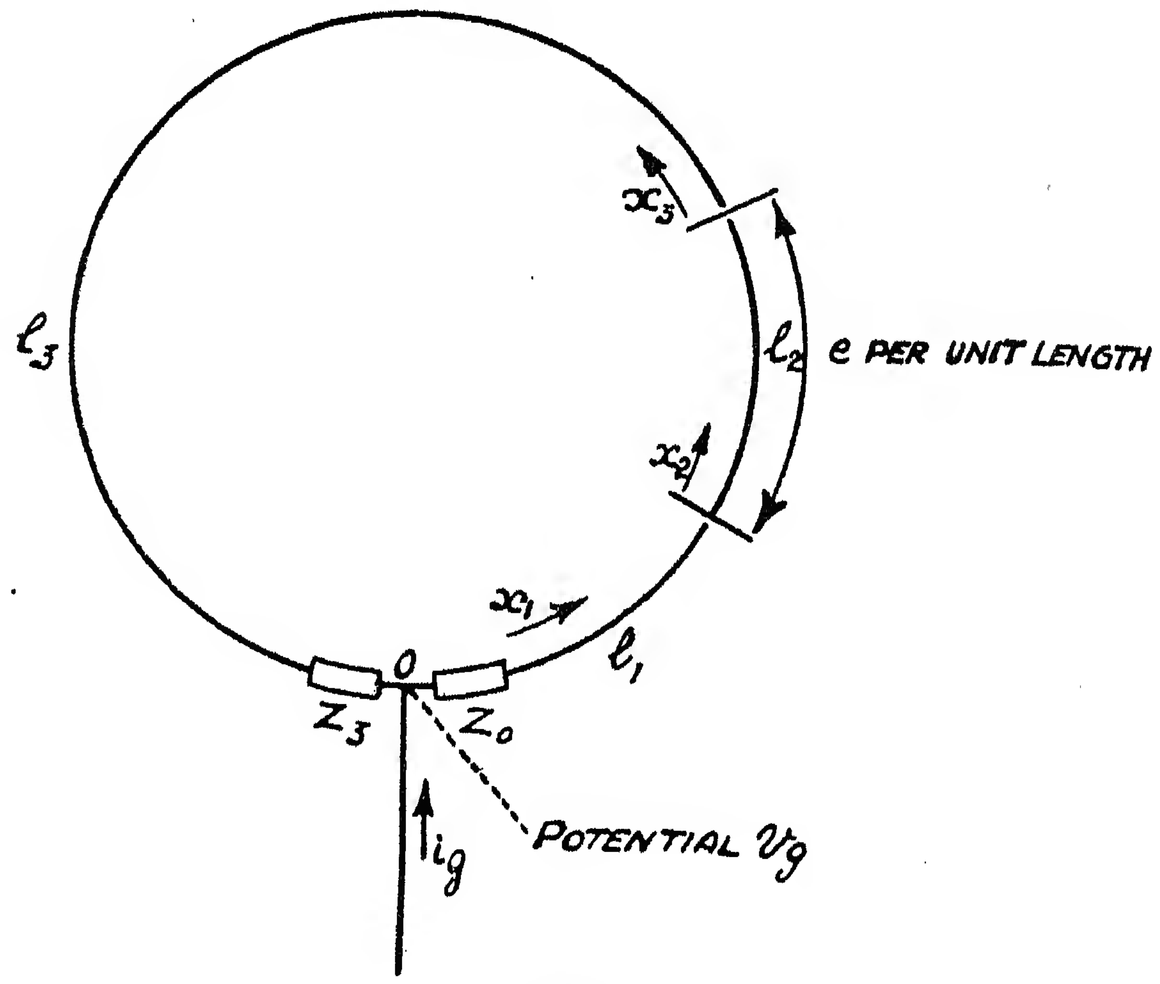

Fig. 1

in so-called balanced or symmetrical systems, or either may be zero. In general one point on these tuning impedances (e.g. the mid-point in a balanced system) will be connected either directly to earth or to the "earthy" point of a receiver or other measuring equipment. There may be, and in general will be, current in any such connection. Moreover, this point cannot in general be assumed to be at earth potential. It will, indeed, appear in the analysis that even if the frame is isolated at all points from earth the mid-point is not, in general, a node of potential, and some finite value must therefore be assumed for its potential. Again, if connected to earth, there may be, and generally will be, an e.m.f. induced in the earth lead by the incident field. The "earthed" point is thus assumed to be at a potential v_g above earth, and a current i_g is assumed to flow in the lead or connection to the "earthed" point.

As explained in Section (2), the conductor is assumed to have a uniform R, L, and C, per unit length. The current co-ordinates x, with suffixes 1, 2, 3, refer to distances along l_1, l_2, l_3, respectively. The instantaneous values of current i and potential v will be similarly distinguished. In addition, suffixes 0 and 1 will denote

initial and final boundary values, i.e. i_{20} and i_{21} are values of i_2 at $x_2 = 0$ and $x_2 = l_2$.

The symbols i and v are to be interpreted as rotating vectors, and e as a rotating vector $e\epsilon^{j\omega t}$. Any constants in the solution will thus have the character of vectors or of vector operators.

(4) ANALYSIS OF THE BASIC SYSTEM

For the parts l_1 and l_3 the appropriate differential equations are

$$(R + j\omega L)i = -\frac{\partial v}{\partial x} \quad . \quad . \quad . \quad (4.01)$$

$$j\omega Cv = -\frac{\partial i}{\partial x} \quad . \quad . \quad . \quad (4.02)$$

with suffixes 1 and 3. For the part l_2 it is necessary to include the e.m.f. e per unit length, giving

$$(R + j\omega L)i_2 = -\frac{\partial v_2}{\partial x_2} + e \quad . \quad . \quad (4.03)$$

and

$$j\omega Cv_2 = -\frac{\partial i_2}{\partial x_2} \quad . \quad . \quad . \quad (4.04)$$

The solutions of these are well known and can be written

$$i = A \sinh Px + B \cosh Px \quad . \quad . \quad . \quad (4.05)$$

$$v = -Z(B \sinh Px + A \cosh Px) \quad . \quad . \quad (4.06)$$

with suffixes 1 and 3 for l_1 and l_3, and

$$i_2 = A_2 \sinh Px_2 + B_2 \cosh Px_2 + \frac{e}{PZ} \quad . \quad (4.07)$$

$$v_2 = -Z(B_2 \sinh Px_2 + A_2 \cosh Px_2) \quad . \quad (4.08)$$

for l_2. In the above

$$P^2 = (R + j\omega L)j\omega C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.09)$$

$$Z^2 = \frac{R + j\omega L}{j\omega C} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.10)$$

For the evaluation of the six unknown constant vectors A, B, there are the following boundary conditions:

$$\left.\begin{aligned} v_{10} &= -Z_0 i_{10} + v_g \\ v_{20} &= v_{11} \\ v_{30} &= v_{21} \\ v_{31} &= Z_3 i_{31} + v_g \\ i_{11} &= i_{20} \\ i_{21} &= i_{30} \end{aligned}\right\} \quad . \quad . \quad . \quad (4.11)$$

The detailed analysis, though lengthy, is quite straightforward and need not be given in full. The results obtained are:—

$$i_0 \frac{\sinh P(a_0 + a_3 + l)}{\sinh Pa_0} = \frac{2e}{PZ} \sinh \frac{Pl_2}{2} \sinh P\left(a_3 + l_3 + \frac{l_2}{2}\right) + \frac{2v_g}{Z} \sinh \frac{Pl}{2} \cosh P\left(a_3 + \frac{l}{2}\right) \quad . \quad (4.12)$$

and

$$i_3 \frac{\sinh P(a_0 + a_3 + l)}{\sinh Pa_3} = \frac{2e}{PZ} \sinh \frac{Pl_2}{2} \sinh P\left(a_0 + l_1 + \frac{l_2}{2}\right) - \frac{2v_g}{Z} \sinh \frac{Pl}{2} \cosh P\left(a_0 + \frac{l}{2}\right) \quad . \quad (4.13)$$

In the above, l is the total length of the conductor, and i_0 is written for i_{10} and i_3 for i_{31}, that is, i_0 and i_3 are the currents through Z_0 and Z_3 respectively. Also the impedances Z_0 and Z_3 are expressed as equivalent real or complex lengths of line a_0 and a_3 by the transformations

$$Z_0 = Z \coth Pa_0$$

and

$$Z_3 = Z \coth Pa_3 \quad . \quad . \quad . \quad (4.14)$$

All the formulae appropriate to rectangular or circular loops, with balanced or unbalanced tuning, can be derived, by suitable specialization, from equations (4.12) and (4.13).

It will be demonstrated that the simplest and most practical short-wave closed-aerial system is that in which complete circuit symmetry is maintained, and Sections (5) to (13) are devoted to this system.

(5) SYMMETRICAL SYSTEMS

The symmetrical or balanced system is defined by

$$Z_3 = Z_0$$

i.e.

$$a_3 = a_0 \quad . \quad . \quad . \quad . \quad (5.1)$$

The basic equations become

$$i_0 \frac{\sinh P(2a_0 + l)}{\sinh Pa_0} = \frac{2e}{PZ} \sinh \frac{Pl_2}{2} \sinh P\left(a_0 + l_3 + \frac{l_2}{2}\right) + \frac{2}{Z} v_g \sinh \frac{Pl}{2} \cosh P\left(a_0 + \frac{l}{2}\right) \quad . \quad (5.2)$$

and

$$i_3 \frac{\sinh P(2a_0 + l)}{\sinh Pa_0} = \frac{2e}{PZ} \sinh \frac{Pl_2}{2} \sinh P\left(a_0 + l_1 + \frac{l_2}{2}\right) - \frac{2}{Z} v_g \sinh \frac{Pl}{2} \cosh P\left(a_0 + \frac{l}{2}\right) \quad . \quad (5.3)$$

(6) RECTANGULAR FRAME: BALANCED TUNING

Consider the system illustrated in Fig. 2. Let i_0, i_3 and i_0', i_3', be the components of current due to the intensities $e\epsilon^{-j\theta}$ and $-e\epsilon^{j\theta}$ respectively, where $\theta = 2\pi b/\lambda$. These currents can be determined directly from (5.2) and (5.3) by appropriate substitutions for l_1, l_2, and l_3, in terms of the height h and width $2b$ of the frame, i.e.

$$l_1 = b,\ l_2 = h, \text{ and } l_3 = 3b + h.$$

Hence

$$l_3 + \frac{l_2}{2} = 3b + 3\frac{h}{2} = \frac{3l}{4}$$

and

$$l_1 + \frac{l_2}{2} = b + \frac{h}{2} = \frac{l}{4} \quad . \quad . \quad . \quad . \quad (6.01)$$

for the intensity $+e\epsilon^{-j\theta}$, and similarly for $-e\epsilon^{j\theta}$. Thus

$$i_0 = A\epsilon^{-j\theta} \sinh P\left(a_0 + \frac{3l}{4}\right) + Bv_g \quad . \quad . \quad (6.02)$$

$$i_0' = -A\epsilon^{j\theta} \sinh P\left(a_0 + \frac{l}{4}\right) + Bv_g \quad . \quad . \quad (6.03)$$

$$i_3 = A\epsilon^{-j\theta} \sinh P\left(a_0 + \frac{l}{4}\right) - Bv_g \quad . \quad . \quad (6.04)$$

$$i_3' = -A\epsilon^{j\theta} \sinh P\left(a_0 + \frac{3l}{4}\right) - Bv_g \quad . \quad . \quad (6.05)$$

where A and B are constant vector operators given by

$$A = \frac{2e}{PZ}\sinh\frac{Ph}{2} \Big/ \left[\frac{\sinh P(2a_0 + l)}{\sinh Pa_0}\right] \quad . \quad . \quad . \quad (6.06)$$

and

$$B = \frac{2}{Z}\sinh\frac{Pl}{2}\cosh P\left(a_0 + \frac{l}{2}\right) \Big/ \left[\frac{\sinh P(2a_0 + l)}{\sinh Pa_0}\right] \quad (6.07)$$

When the intensities act simultaneously on the frame, the total currents will be given by the addition of the formulae in pairs. (It must be remembered, however, that v_g is a quantity, at present undetermined, dependent on i_0, i_0', i_3, and i_3', and in the addition of these formulae the terms in v_g are not added but merely replaced by a similar symbol for subsequent determination.)

The Asymmetry of the Balanced Frame Aerial

One immediate conclusion can be drawn from the general form of equations (6.02) to (6.05), namely that the balanced frame aerial is electrically unsymmetrical

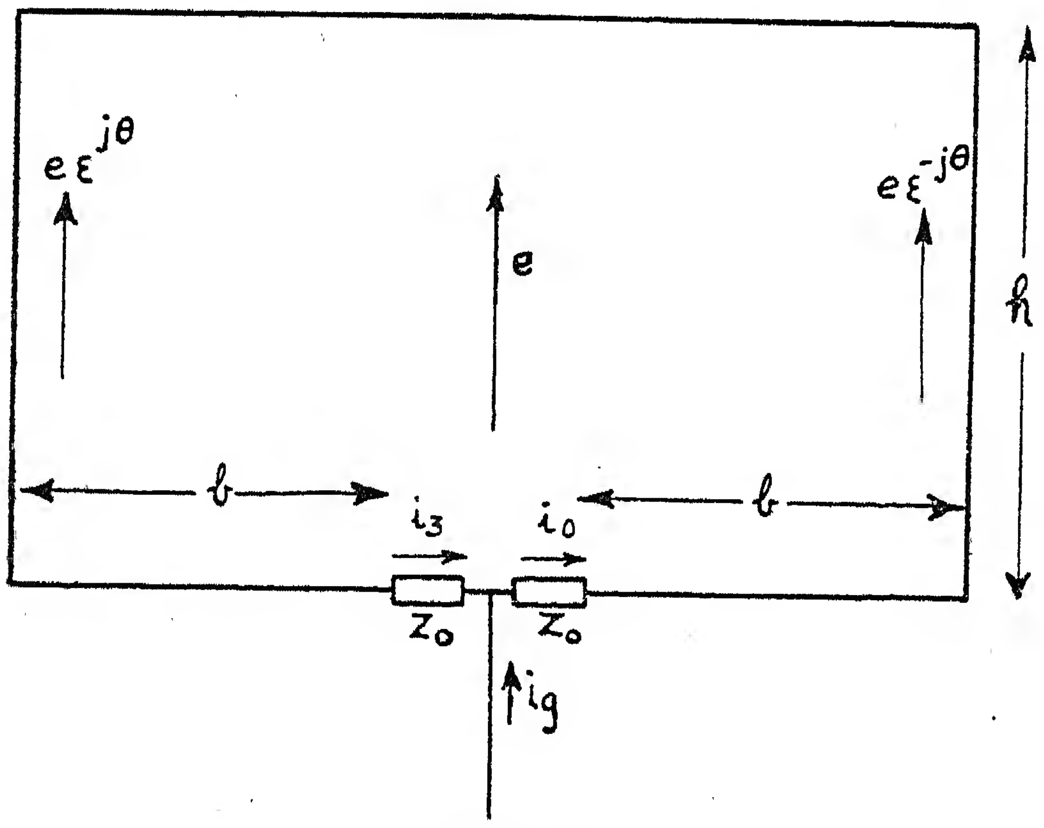

Fig. 2

in general, in the sense that the potential differences across the two equal halves of the tuning impedance are not in general equal in magnitude and phase. The possibility of this was of course implied in the assumption of a current in the connection to the mid-point of the tuning impedance, but it remains to be shown that this current will in general exist.

Suppose, for example, that the mid-point is actually connected to earth by a lead so short that its impedance and any e.m.f. induced in it by the field can be neglected. Analytically, this is equivalent to putting $v_g = 0$ in equations (6.02) to (6.05). The circuit system is still completely balanced, but there will nevertheless be a current in this earth lead and a consequent small inequality of the potential differences across the two halves of the tuning impedance.

The general character of the vector system represented by i_0, i_0', i_3, and i_3', is illustrated in Fig. 3(*a*), which shows that the vector sums $(i_0 + i_0')$ and $(i_3 + i_3')$ are equal in magnitude but differ in phase. Thus in general the potential difference across the whole tuning impedance will not be twice the potential difference across either half of it. This asymmetry must obviously be a consequence of the fact that the complete system of circuit and field is not in fact symmetrical so far as a circulation round the loop is concerned. This asymmetry is able to manifest itself at the tuning impedances. In fact the different arguments of the hyperbolic functions in, for example, (6.02) and (6.03) correspond to the fact that the individual e.m.f.'s are not symmetrically disposed in relation to the tuning impedances.

It will be shown later that when the loop is tuned

$$a_0 = \tfrac{1}{4}n\lambda - \tfrac{1}{2}l; \quad n = 1, 3, 5, \text{ etc.} \quad . \quad (6.08)$$

Under these conditions

$$a_0 + \tfrac{1}{4}l = \tfrac{1}{4}n\lambda - \tfrac{1}{4}l$$

and

$$a_0 + \tfrac{3}{4}l = \tfrac{1}{4}n\lambda + \tfrac{1}{4}l \quad . \quad . \quad . \quad (6.09)$$

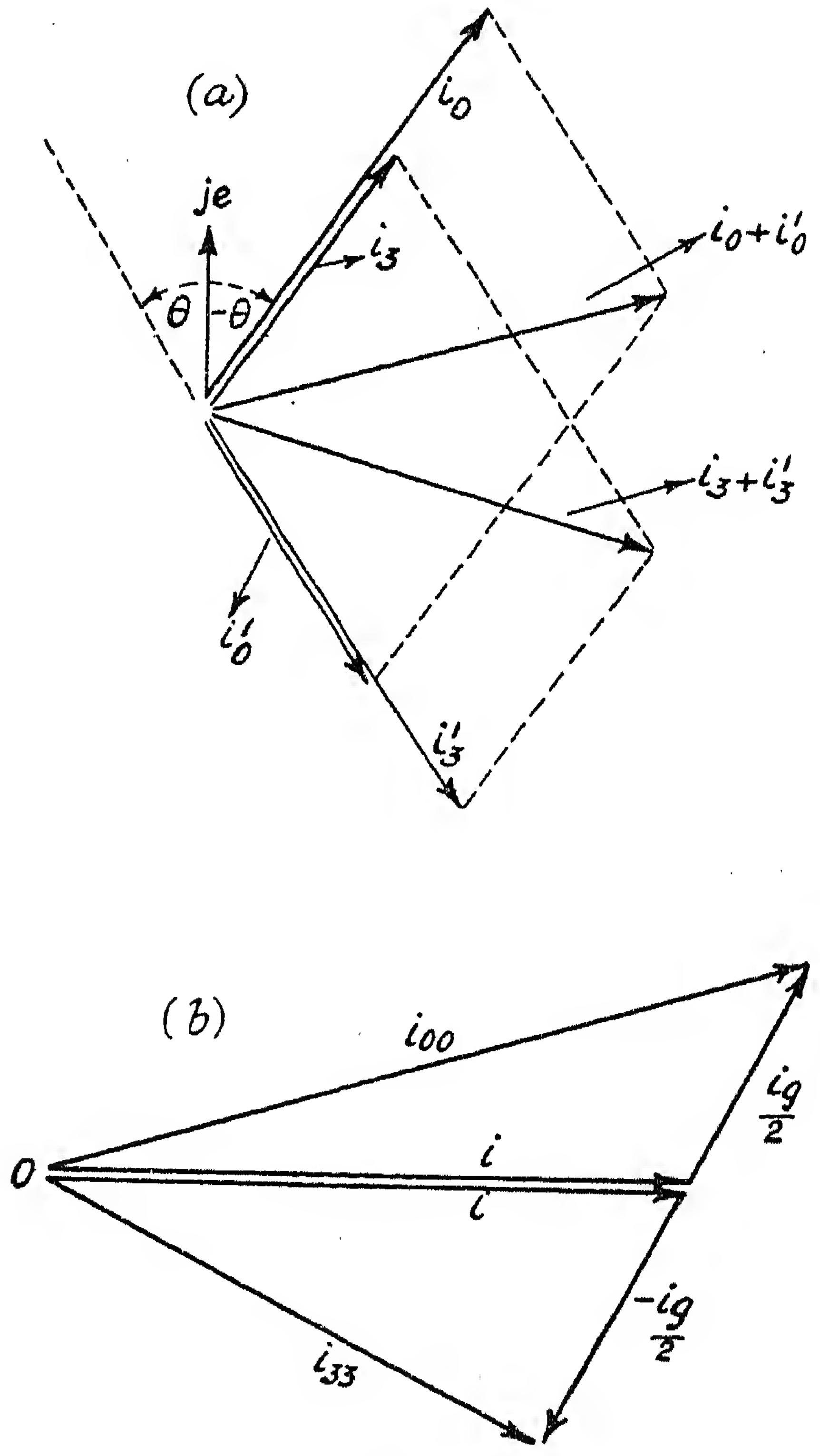

Fig. 3

and the sinh terms become equal in phase and magnitude except for small terms due to attenuation. Thus when the loop is tuned the currents $(i_0 + i_0')$ and $(i_3 + i_3')$ through the two tuning impedances become practically equal in phase and magnitude, except for a very small and probably negligible effect due to differences of attenuation in the lengths $\frac{1}{4}l$ and $\frac{3}{4}l$ of the conductor.

It is important to remember, however, that this is true only on the assumption that the only e.m.f.'s acting on the system are those induced in the loop by the incident field. It is true, that is to say, for a very short lead to earth or to the "earthy" point of a receiver. Suppose, however, there is a relatively long lead from the mid-point. Then there may be induced in this lead an e.m.f. which may be of the same order as, or even greater than, the e.m.f.'s induced in the sides of the loop, and

there may be in consequence an appreciable current in the mid-point connection due to this e.m.f. If the loop is truly balanced this current will divide equally at the mid-point, adding to the current through one half and subtracting from the current through the other half. Thus we may have a state of affairs somewhat as shown in Fig. 3(*b*), and again the potentials across each half of the tuning impedance will be unequal, possibly both in magnitude and phase.

The effect of the mid-point current is of course eliminated if the output voltage be measured as the vector sum of the voltages across each half of the tuning impedance. This point is shown in analytical detail below, and the practical aspect of the matter is referred to again in Section (16). It may be pointed out, however, that these considerations do not apply exclusively to the balanced loop as a means of field-strength measurement. A balanced dipole system may be subject to the same considerations in respect of e.m.f.'s, if any, induced in a conductor connected to the mid-point of any tuning impedance associated with it.

The addition of (6.02), (6.03) and (6.04), (6.05) gives for the total currents $(i_0 + i_0')$ and $(i_3 + i_3')$ due to the simultaneous action of the e.m.f.'s induced in the two sides of the frame:—

$$i_0 + i_0' = A\left\{2\cosh P\left(a_0 + \frac{l}{2}\right)\sinh\frac{Pl}{4}\cos\theta - 2j\sinh P\left(a_0 + \frac{l}{2}\right)\cosh\frac{Pl}{4}\sin\theta\right\} + Bv_g \quad . \quad (6.10)$$

and

$$i_3 + i_3' = A\left\{-2\cosh P\left(a_0 + \frac{l}{2}\right)\sinh\frac{Pl}{4}\cos\theta - 2j\sinh P\left(a_0 + \frac{l}{2}\right)\cosh\frac{Pl}{4}\sin\theta\right\} - Bv_g \quad . \quad (6.11)$$

[In these equations, as already pointed out, v_g is as yet undetermined, and will not have the same value as in equations (6.02) to (6.05).]

The first point to note is that the sum of the combined currents (and therefore the total potential difference across the tuning impedance) is independent of v_g. This is otherwise obvious. It is not immediately obvious that it is also independent of i_g, the current in the "earth" connection, but this is clear if we assume, in accordance with the circuit symmetry, that the "earth" current divides equally at the mid-point. Writing i_{00} and i_{33} for the combined currents, then, as illustrated in Fig. 4,

$$i = \tfrac{1}{2}(i_{00} + i_{33}) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6.12)$$

and

$$i_g = i_{00} - i_{33} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6.13)$$

$$i_{00} = \tfrac{1}{2}(i_{00} + i_{33}) + \tfrac{1}{2}(i_{00} - i_{33}) = i + \tfrac{1}{2}i_g \quad (6.14)$$

and

$$i_{33} = \tfrac{1}{2}(i_{00} + i_{33}) - \tfrac{1}{2}(i_{00} - i_{33}) = i - \tfrac{1}{2}i_g \quad (6.15)$$

Thus i can be regarded as a circulating current flowing through the two halves of the impedance in series, while an "earth" current i_g flows through the two halves in parallel, $\tfrac{1}{2}i_g$ flowing through each half. From (6.10) and (6.11) we have

$$i = -2jA\sinh P\left(a_0 + \frac{l}{2}\right)\cosh\frac{Pl}{4}\sin\theta \quad . \quad (6.16)$$

and

$$i_g = 4A\cosh P\left(a_0 + \frac{l}{2}\right)\sinh\frac{Pl}{4}\cos\theta + 2Bv_g \quad (6.17)$$

From (6.17) it can be seen, as already stated, that i_g is not zero in general even when v_g is taken to be zero, and further that, apart from any variation of v_g, a value of θ which makes i a maximum will make i_g a minimum.

Inserting in (6.16) and (6.17) the values of A and B from (6.06) and (6.07) gives

$$i\,\frac{\cosh P(a_0 + \frac{1}{2}l)}{\sinh Pa_0} = \frac{-2je}{PZ}\sinh\frac{Ph}{2}\cosh\frac{Pl}{4}\sin\theta \quad (6.18)$$

and

$$i_g\,\frac{\sinh P(a_0 + \frac{1}{2}l)}{\sinh P\,a_0} = \frac{4e}{PZ}\sinh\frac{Ph}{2}\sinh\frac{Pl}{4}\cos\theta + \frac{2v_g}{Z}\sinh\frac{Pl}{2} \quad . \quad . \quad . \quad (6.19)$$

It is shown in the next Section that these formulae admit of a simple physical interpretation.

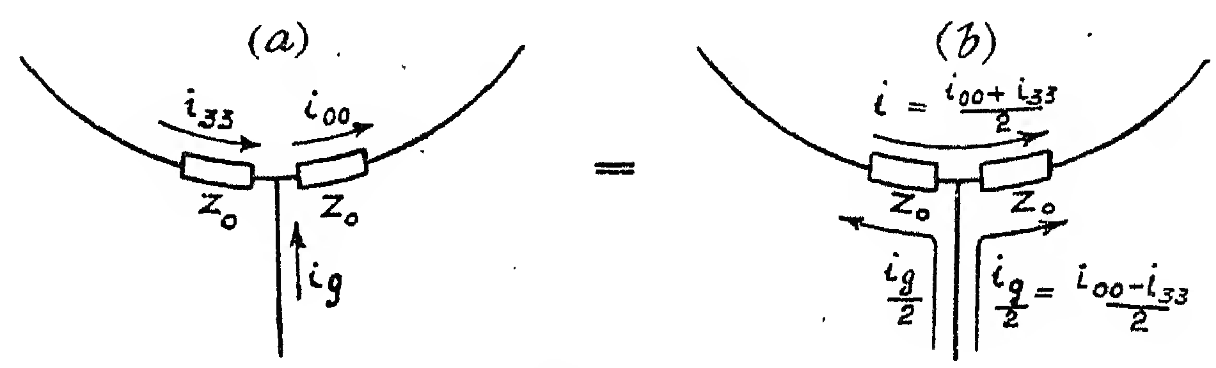

Fig. 4

(7) PHYSICAL INTERPRETATION OF FORMULAE

Formula (6.18) admits of a very simple physical interpretation. Replacing $\coth Pa_0$ by Z_0/Z and θ by $2\pi b/\lambda$ gives

$$i\left\{2Z_0 + 2Z\tanh\frac{Pl}{2}\right\} = \frac{-4je}{P}\,\frac{\cosh(\frac{1}{4}Pl)\sinh(\frac{1}{2}Ph)\sin(2\pi b/\lambda)}{\cosh(\frac{1}{2}Pl)} \quad (7.01)$$

or

$$i = \frac{e_e}{2Z_0 + Z_e} \quad . \quad . \quad . \quad . \quad (7.02)$$

where

$$e_e = \frac{-4je}{P}\,\frac{\cosh(\frac{1}{4}Pl)\sinh(\frac{1}{2}Ph)\sin(2\pi b/\lambda)}{\cosh(\frac{1}{2}Pl)} \quad (7.03)$$

and

$$Z_e = 2Z\tanh(\tfrac{1}{2}Pl) \quad . \quad . \quad . \quad . \quad . \quad . \quad (7.04)$$

Thus the circulating current i can be regarded as due to an effective e.m.f. e_e acting in a circuit consisting of the tuning impedance $2Z_0$ in series with an effective aerial impedance Z_e, where both e_e and Z_e are quite independent of the tuning impedance.

It will be shown, moreover, that if the loop is considered to be small in dimensions compared with λ, these formulae reduce to those given in the first section for small aerials. Thus, when l and h are small compared with λ,

$$\cosh(\tfrac{1}{2}Pl) \to \cosh(\tfrac{1}{4}Pl) \to 1$$

$$\sinh(\tfrac{1}{2}Ph) \to \tfrac{1}{2}Ph$$

and

$$\sin\frac{2\pi b}{\lambda} \to \frac{2\pi b}{\lambda} \quad . \quad . \quad . \quad . \quad (7.05)$$

and $$e_e \to -\frac{4je}{P}\cdot\frac{Ph}{2}\cdot\frac{2\pi b}{\lambda}$$

$$= -j\frac{2\pi}{\lambda}Ae \quad . \quad . \quad . \quad . \quad . \quad (7.06)$$

i.e. $$|e_e| = \frac{2\pi}{\lambda}A|e| \quad . \quad . \quad . \quad . \quad . \quad . \quad (7.07)$$

where $A = 2bh$ = area of loop.

Further, $$2Z\tanh(\tfrac{1}{2}Pl) \to PZl$$

$$= (R + j\omega L)l$$

$$= R_a + j\omega L_a \quad . \quad . \quad . \quad . \quad . \quad (7.08)$$

where R_a and L_a are the total resistance and inductance of the loop. When the aerial is tuned

$$2Z_0 + j\omega L_a = 0 \quad . \quad . \quad . \quad (7.09)$$

i.e. $$i = \frac{-j\frac{2\pi}{\lambda}Ae}{R_a} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7.10)$$

and $$v = 2Z_0 i = -j\omega L_a i$$

$$= -\frac{\omega L_a}{R_a}\cdot\frac{2\pi}{\lambda}\cdot A.e$$

or $$|v| = \frac{\omega L_a}{R_a}|e_e| \quad . \quad . \quad . \quad . \quad . \quad . \quad (7.11)$$

The formula for the earth current i_g admits of a similar interpretation. The same process gives

$$i_g\left\{\frac{Z}{2}\coth\frac{Pl}{2} + \frac{Z_0}{2}\right\} = \frac{e}{P}\cdot\frac{\sinh(Ph/2)}{\cosh(Pl/4)}\cos\frac{2\pi b}{\lambda} + v_g \quad (7.12)$$

In this case the effective aerial impedance is $\frac{1}{2}(Z\coth\frac{1}{2}Pl)$ (i.e. two paths in parallel) and the added impedance is that of two impedances Z_0 in parallel, while the effective e.m.f. is a term due to e, plus the assumed potential of the mid-point, i.e. v_g.

(8) DETERMINATION OF THE MID-POINT POTENTIAL AND EARTH-LEAD CURRENT

If, in the case illustrated in Fig. 2, the earth lead, of length g, is assumed to have the same value of P as the conductor forming the frame aerial, is earthed at its lowest point, and is vertical and subject to a field intensity e per unit length, it is easily shown, by the methods used in Section (4), that

$$v_g = -Z\tanh Pg\left(i_g - \frac{e}{PZ}\right) \quad . \quad . \quad (8.1)$$

In combination with (7.12) this gives, for i_g,

$$i_g\left(\frac{Z_0}{2} + \frac{Z}{2}\coth\frac{Pl}{2} + Z\tanh Pg\right)$$

$$= \frac{e}{P}\left(\frac{\sinh(Ph/2)}{\cosh(Pl/4)}\right)\cos\frac{2\pi b}{\lambda} + \tanh Pg \quad (8.2)$$

Alternatively, the mid-point may not be connected to earth directly. It might, for example, be connected by a short lead to the "earthy" point of a receiver, of which the capacitance to earth can be represented as an impedance Z_g.

In this case

$$v_g = -Z_g i_g \quad . \quad . \quad . \quad . \quad (8.3)$$

and

$$i_g\left(\frac{Z_0}{2} + \frac{Z}{2}\coth\frac{Pl}{2} + Z_g\right) = \frac{e}{P}\cdot\frac{\sinh(Ph/2)}{\cosh(Pl/4)}\cos\frac{2\pi b}{\lambda} \quad (8.4)$$

Even in this case, however, i_g will not necessarily be negligible, since the combined impedance term on the left of (8.4) is clearly capable of resonance conditions, as also is the e.m.f. on the right of (8.4).

Finally, as a point of academic interest, if it be assumed that the frame can be so disposed that there is no current from the mid-point to earth, i.e. if there is no connection from the mid-point to earth, and any apparatus connected to the mid-point has negligible capacitance to earth, then, from (7.12),

$$v_g = -\frac{e}{P}\frac{\sinh(Ph/2)}{\cosh(Pl/4)}\cos\frac{2\pi b}{\lambda} \quad . \quad . \quad (8.5)$$

The formula for i is not affected, but it will be found that the substitution of this value for v_g in the formulae for i_{00} and i_{33} makes these currents equal in phase and magnitude, which is otherwise obvious.

The physical significance of the finite value of v_g given by (8.5) is that the mid-point of a balanced frame aerial completely isolated from earth is not in general a node of potential, though, from (8.5), it becomes a node of potential if the width $2b$ is an odd number of half wavelengths. This is in agreement with the conclusions of Palmer, Taylor, and Witty, based on considerations of current distribution.*

(9) THE MEASUREMENT OF THE RESONANCE FACTOR

The term "resonance factor" is here used, for want of any existing and generally recognized term, to denote the ratio between v, the potential difference across the tuning circuit, and e_e, the effective e.m.f. induced in the loop. It is thus a generalization of the term Q or "magnification factor" as applied to uniform-current circuits.

In the case of closed-coil aerials small compared with the wavelength, this factor is usually determined by one of two methods, (a) reactance variation, (b) insertion of a small known e.m.f. and measurement of the corresponding terminal potential difference.

It will be desirable to determine whether these or similar methods are valid for cases in which the coil aerial is not small compared with the wavelength, and in which therefore the current distribution is not uniform.

(a) Reactance Variation

It has been shown in Section (7) that for a rectangular frame aerial the circulating current i can be regarded as due to an effective e.m.f. e_e acting in series with a variable tuning impedance $2Z_0$ and an aerial impedance Z_e, i.e.

$$i = \frac{e_e}{2Z_0 + Z_e} \quad . \quad . \quad . \quad . \quad (9.01)$$

* *Proceedings of the Physical Society*, 1934, vol. 46, p. 76.

In this expression e_e and Z_e are independent of Z_0, but both depend on frequency. At any given frequency, however, Z_e can be regarded as consisting of an effective resistance R_e in series with an effective reactance X_e. The tuning impedance may take the form of a symmetrical condenser, and if C_0 be the magnitude of the two halves in series

$$2Z_0 = \frac{1}{j\omega C_0} \quad . \quad . \quad . \quad . \quad (9.02)$$

The exact tuning condition for resonance of the potential difference v across C_0 is given by

$$\omega C_0 = \frac{X_e}{Z_e^2} \quad . \quad . \quad . \quad . \quad (9.03)$$

where
$$Z_e^2 = R_e^2 + X_e^2 \quad . \quad . \quad . \quad . \quad (9.04)$$

and at resonance
$$\left|\frac{v}{e_e}\right|^2 = \frac{Z_e^2}{R_e^2} \quad . \quad . \quad . \quad . \quad . \quad (9.05)$$

If C_0 be adjusted to a new value C_0' for which the condenser potential difference is reduced to $1/\sqrt{2}$ of its resonance-value, then

$$\frac{1}{Z_e^2} \cdot \frac{1}{\left(\frac{R_e}{Z_e^2}\right)^2 + \left(\omega C_0' - \frac{X_e}{Z_e^2}\right)^2} = \frac{1}{2} \cdot \frac{Z_e^2}{R_e^2} \quad . \quad (9.06)$$

whence
$$\left(\omega C_0' - \frac{X_e}{Z_e^2}\right)^2 = \frac{R_e^2}{Z_e^4} \quad . \quad . \quad . \quad (9.07)$$

or
$$\omega C_0' - \frac{X_e}{Z_e^2} = \pm \frac{R_e}{Z_e^2} \quad . \quad . \quad (9.08)$$

If C_0' and C_0'' be the two values of C_0 which satisfy this condition

$$\omega C_0' - \frac{X_e}{Z_e^2} = \frac{R_e}{Z_e^2} \quad . \quad . \quad . \quad . \quad (9.09)$$

and
$$\omega C_0'' - \frac{X_e}{Z_e^2} = -\frac{R_e}{Z_e^2} \quad . \quad . \quad . \quad . \quad (9.10)$$

or, putting
$$C_0' - C_0'' = 2\delta C_0 \quad . \quad . \quad . \quad (9.11)$$

$$\omega \delta C_0 = \frac{R_e}{Z_e^2} \quad . \quad . \quad . \quad . \quad (9.12)$$

Also
$$\omega C_0 = \frac{X_e}{Z_e^2} \quad . \quad . \quad . \quad . \quad (9.13)$$

The combination of (9.05), (9.12), and (9.13), gives

$$\left|\frac{v}{e_e}\right| = \frac{C_0}{\delta C_0}\left(1 + \frac{\delta C_0^2}{C_0^2}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad (9.14)$$

In general δC_0^2 will be quite negligible compared with C_0^2, and

$$\left|\frac{v}{e_e}\right| = \frac{C_0}{\delta C_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9.15)$$

Thus the resonance variation method is valid in spite of the non-uniform current distribution, provided it be carried out by variation of the tuning capacitance *and not by variation of frequency*. A formula appropriate to variation of frequency could probably be determined, but it would be very complicated and probably less accurate.

(b) Determination by Inserted E.M.F.

The validity of this method can be examined by reference to (5.12), i.e.

$$i\frac{\cosh P(a_0 + \frac{1}{2}l)}{\sinh Pa_0} = \frac{e}{PZ}\cosh\frac{P(l_3 - l_1)}{2}\sinh\frac{Pl_2}{2}$$

which can be put in the form

$$i = \frac{e_e}{Z_0 + Z_e}$$

where
$$e_e = \frac{\frac{2e}{P}\sinh(\frac{1}{2}Pl_2)\cosh\left[\frac{1}{2}P(l_3 - l_1)\right]}{(\cosh\frac{1}{2}Pl)} \quad . \quad (9.16)$$

Suppose now that the inserted e.m.f. e_0 be located at the centre of the loop remote from the tuning circuit. This condition is represented by reducing the length l_2 to zero with the condition

$$\underset{l_2 \to 0}{lt.} \frac{2e}{P}\sinh\frac{Pl_2}{2} = \underset{l_2 \to 0}{lt.} el_2 = e_0 \quad . \quad (9.17)$$

Then, since for this condition $l_1 = l_3$,

$$e_e = \frac{e_0}{\cosh(\frac{1}{2}Pl)} \quad . \quad . \quad . \quad (9.18)$$

Thus the effective series e.m.f. is greater than e_0. For example, if $l = \frac{1}{5}\lambda$, $\cosh(\frac{1}{2}Pl) \simeq 0{\cdot}80$ and the resonance factor would be over-estimated by some 20 % if this method were used, and for $l = \frac{1}{4}\lambda$ the error would be 30%.

However, by applying the same process it is easy to show that if the e.m.f. be inserted adjacent to the tuning reactance, i.e. $l_1 = 0$, $l_3 = l$, then the effective series e.m.f. is equal to e_0. *Thus the inserted-e.m.f. method can be used, regardless of the relation of l to λ, provided the e.m.f. be inserted adjacent to the tuning circuit and not at the centre of the loop remote from the tuning circuit.* (This assumes that the output voltage is measured across the tuning circuit. The case, which sometimes occurs in practice, when the loop is tuned by a condenser in the top centre of the loop, and the output is measured across a fixed impedance at the bottom centre, would need separate consideration on the lines indicated.)

(10) DETAILED ANALYSIS OF RECTANGULAR FRAME WITH BALANCED TUNING

The following relationships are listed for reference.

$$P = \sqrt{[(R + j\omega L)j\omega C]}$$
$$= \alpha + j\beta$$

where, assuming R^4 is small compared with $\omega^4 L^4$

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10.01)$$

$$\beta = \omega\sqrt{(LC)}\left(1 + \frac{R^2}{8\omega^2 L^2}\right) \quad . \quad . \quad . \quad (10.02)$$

Therefore, neglecting $R^2/(8\omega^2L^2)$ compared with 1

$$\beta = \omega\sqrt{(LC)} = \frac{2\pi}{\lambda} \quad . \quad . \quad . \quad . \quad . \quad (10.03)$$

Also
$$Z = \sqrt{\frac{L}{C}}\left\{\left(1 + \frac{R^2}{8\omega^2L^2}\right) - j\frac{R}{2\omega L}\right\} \quad . \quad (10.04)$$

$$\simeq \sqrt{\frac{L}{C}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10.05)$$

For the type of conductor contemplated in this analysis, the "characteristic impedance" Z will usually be about 600 ohms.

In the following analysis it is assumed that $\beta = 2\pi/\lambda$ and that $2\alpha\lambda$ is so small that $\cosh 2\alpha\lambda \simeq 1$ and $\sinh 2\alpha\lambda \simeq 2\alpha\lambda$.

The detailed examination of the rectangular frame is most conveniently related to the formulae

$$e_e = \frac{-4je}{P}\frac{\cosh(\frac{1}{4}Pl)\sinh(\frac{1}{2}Ph)\sin 2\pi b/\lambda}{\cosh(\frac{1}{2}Pl)} \quad (10.06)$$

$$Z_e = 2Z\tanh(\tfrac{1}{2}Pl) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10.07)$$

and

$$i_g\left(\frac{Z_0}{2} + \frac{Z}{2}\coth\frac{Pl}{2} + Z\tanh P_g\right)$$
$$= \frac{e}{P}\left[\frac{\sinh(\frac{1}{2}Ph)}{\cosh(\frac{1}{4}Pl)}\cos 2\pi b/\lambda + \tanh P_g\right] \quad (10.08)$$

The formula for i_g will make it possible to estimate the difference between the potential differences across the two halves of the tuning impedance, which can be expressed fractionally in the form

$$\frac{v_0 - v_3}{v} = \frac{i_0 - i_3}{2i} = \frac{1}{2}\cdot\frac{i_g}{i} \quad . \quad . \quad (10.09)$$

(a) Small Aerial

For the common case in which l is small compared with λ, but not negligibly small, the ratio of the effective e.m.f. to that calculated by the simple formula given in Section (1) is very approximately

$$\left|\frac{e_e}{e'_e}\right| = \frac{\sin \pi h/\lambda}{\pi h/\lambda}\,\frac{\sin 2\pi b/\lambda}{2\pi b/\lambda}\,\frac{\cos \pi l/2\lambda}{\cos \pi l/\lambda} \quad . \quad (10.10)$$

Taking, for example, a square loop with

$$2b = h = \lambda/16;\ \text{i.e. } l = \lambda/4$$

$$\left|\frac{e_e}{e'_e}\right| = \left(\frac{\sin \pi/16}{\pi/16}\right)^2\frac{\cos \pi/8}{\cos \pi/4} = 1\cdot 23 \quad . \quad (10.11)$$

In this case, therefore, the use of the simpler formula would lead to an over-estimation of field strength of about 23 %.

It is difficult to estimate the significance of i_g in such a case, but if it be assumed in the first instance that the frame is earthed at its mid-point,

$$\frac{i_g}{2i} = \frac{j}{2}\cdot\frac{\cosh(\frac{1}{2}Pl)}{\cosh^2(\frac{1}{4}Pl)}\cot\frac{2\pi b}{\lambda}\cdot\frac{Z_0 + Z\tanh(\frac{1}{2}Pl)}{Z_0 + Z\coth(\frac{1}{2}Pl)} \quad (10.12)$$

Now
$$Z_0 + Z\coth\frac{Pl}{2} \simeq \frac{1}{j\omega C_0} + \frac{2Z}{Pl} = \frac{1}{j\omega C_0} + \frac{2}{j\omega C_a} \quad (10.13)$$

where C_a is written for lC, i.e. it is the total aerial capacitance. Also

$$Z_0 + Z\tanh\frac{Pl}{2} \simeq \frac{1}{j\omega C_0} + \frac{R_a}{2}\frac{j\omega L_a}{2} \quad . \quad (10.14)$$

and if the aerial is tuned

$$\frac{1}{j\omega C_0} = \frac{1}{2}j\omega L_a \quad . \quad . \quad . \quad . \quad (10.15)$$

In general $2/(j\omega C_a)$ will be large compared with $1/(j\omega C_0)$.

Therefore
$$\frac{Z_0 + Z\tanh(\frac{1}{2}Pl)}{Z_0 + Z\coth(\frac{1}{2}Pl)} \simeq \frac{1}{4}j\omega C_a R_a \quad . \quad . \quad (10.16)$$

Thus for the numerical case considered

$$\frac{i_g}{2i} = -\frac{1}{8}\left(\frac{\cos \pi/4}{\cos^2 \pi/8}\right)\cot\frac{\pi}{16}\omega C_a R_a$$
$$= -0\cdot 52\ \omega C_a R_a \quad . \quad . \quad . \quad . \quad . \quad . \quad (10.17)$$

But
$$\omega^2 LC = \frac{4\pi^2}{\lambda^2}$$

Therefore for

$$l = \lambda/4, \quad \omega C_a = \frac{\pi^2}{4\omega L_a} \simeq \frac{10}{4}\cdot\frac{1}{\omega L_a}$$

Therefore

$$\frac{i_g}{2i} = -0\cdot 52 \times \frac{10}{4}\left(\frac{R_a}{\omega L_a}\right) = -1\cdot 3\frac{R_a}{\omega L_a} \quad (10.18)$$

Thus the unsymmetrical current is very small compared with the circulating current, and may be 1 or 2 per cent of it in magnitude. If the frame is raised above the surface of the earth, however, and the centre point is connected to earth by a lead, the effective e.m.f. producing the unsymmetrical current will be increased—roughly in the proportion of g to $\frac{1}{2}h$, without a proportionate increase of impedance, and it therefore appears that even with comparatively small earthed frame aerials it cannot safely be assumed that the total tuning-circuit potential difference can be determined by measurement across one side only of the symmetrical tuning system.

It would, however, appear to be permissible to use such a frame without direct connection to earth, and the asymmetry may in practice be reduced in this way, though at the very high frequencies assumed in this analysis the capacitance to earth of the measuring system will, in general, make it difficult to maintain a very high impedance to earth. In practice, if the receiver potential difference is determined by measurement across one half of the tuning impedance it will in general be advisable to compare the values corresponding to the two maxima (by rotation of the frame). Any substantial inequality observed may be the result of the asymmetry discussed above.

(b) Large Frame Aerials

Provided that the theory of the large frame aerial be known there would seem to be no need to restrict the frame dimensions as is the present practice in field-strength measurement. In fact, the use of a large frame may offer some advantages. It will therefore be of

practical interest to consider cases where l may be comparable with or greater than the wavelength of operation.

(1) $l = 0$ to $l = \frac{1}{2}\lambda$

Up to, but not including, $l = \frac{1}{2}\lambda$ there are no resonances of impedance or e.m.f. The effective impedance remains positive (inductive) in character and the system is tunable by a capacitance. The e.m.f. can be calculated by the formulae given.

(2) $l = \frac{1}{2}\lambda$.

$$Z_e \simeq \frac{8Z}{\alpha\lambda} \simeq \frac{8L_a}{C_a R_a} \quad . \quad . \quad . \quad . \quad (10.19)$$

Thus Z_e is very large and resistive. The appropriate tuning system would be a parallel-tuned circuit. The e.m.f. is approximately

$$e_e = \frac{-2\sqrt{2}}{\alpha\lambda}\left(\frac{2\pi}{\lambda}Ae\right)$$

$$= -2\sqrt{(2)}\frac{Z}{R_a}\left(\frac{2\pi}{\lambda}Ae\right) \quad . \quad . \quad (10.20)$$

and may thus be large compared with the e.m.f. calculated by the uniform current formula. Thus the half-wavelength loop may be considered for field strength measurement, though it may be difficult to realize a tuning impedance of sufficient magnitude to make the output or received potential difference a large fraction of the induced e.m.f.

(3) $l = \frac{3}{4}\lambda$.

$$Z_e \simeq -jZ \quad . \quad . \quad . \quad . \quad . \quad . \quad (10.21)$$

i.e. the impedance is fairly large and negative. The e.m.f. will depend on the ratio of $2b$ to h, but will not show any resonant conditions.

(4) $l = \lambda$.

$$Z_e \simeq Z\alpha\lambda \simeq \frac{R_a}{2} \quad . \quad . \quad . \quad . \quad (10.22)$$

Thus the impedance is small and resistive. However, the e.m.f. contains the term $\cosh \frac{1}{4}Pl$, and this reduces to the very small quantity $\frac{1}{4}\alpha\lambda$. Thus the induced e.m.f. will be very small and the configuration appears to have no practical value.

(5) $l = \frac{3}{2}\lambda$.

$$Z_e \simeq \frac{4}{3\alpha\lambda}2Z \simeq \frac{8}{3}\cdot\frac{L_a}{C_a R_a} \quad . \quad . \quad . \quad (10.23)$$

Thus the impedance is similar to that in the $\frac{1}{2}\lambda$ case.

Also $$e_e = j\frac{2\sqrt{2}}{3}\cdot\frac{Z}{R_a}\left(\frac{2e\lambda}{\pi}\sinh\frac{Ph}{2}\sin\frac{2\pi b}{\lambda}\right) \quad . \quad (10.24)$$

and is therefore large in general and depends on the values of b and h. Thus if $2b = \frac{1}{2}\lambda$ and $h = \frac{1}{4}\lambda$

$$e_e = -\frac{2}{3}\cdot\frac{Z}{R_a}\cdot\frac{2e\lambda}{\pi} \quad . \quad . \quad . \quad (10.25)$$

and is therefore large.

(6) $l = 2\lambda$.

$$Z_e \simeq 2\,Z\alpha\lambda \simeq R_a \quad . \quad . \quad . \quad . \quad (10.26)$$

The impedance is therefore small and resistive. The appropriate tuning system is a series-tuned circuit.

$$e_e \simeq \frac{2\lambda e}{\pi}\left(\sinh\frac{Ph}{2}\sin\frac{2\pi b}{\lambda}\right) \quad . \quad . \quad (10.27)$$

and therefore depends on the shape. If the coil is square, i.e. $2b = h = \frac{1}{2}\lambda$

$$e_e \simeq j\frac{2\lambda e}{\pi} = j\frac{le}{\pi} \quad . \quad . \quad . \quad . \quad (10.28)$$

This appears to be a possible configuration for field-strength measurement. For example, the effective e.m.f. would be about 25 times as large as that given by a small coil having a periphery of $\frac{1}{4}\lambda$, and 40 times as large as that given by a coil with a periphery of $\frac{1}{5}\lambda$.

(11) THE LARGE RECTANGULAR FRAME IN RELATION TO DIRECTION-FINDING

It has already been shown that the large frame may be expected to have the advantage of a relatively large "pick-up factor." In relation to direction-finding, however, the important quantity is the sharpness of the minimum. For a vertical wave incident at an angle ϕ to the normal to the plane of the frame

$$\left|e_e\right| = \left|\frac{4_e}{P}\cdot\frac{\cosh(\frac{1}{4}Pl)\sinh(\frac{1}{2}Ph)}{\cosh(\frac{1}{2}Pl)}\cdot\frac{\sin 2\pi b\sin\phi}{\lambda}\right| \quad . \quad (11.1)$$

The sharpness of the minima can be measured by $d|e_e|/d\phi$, i.e.

$$S = \frac{d|e_e|}{d\phi} = \frac{2\lambda e}{\pi}\cdot\frac{\cos 2a\pi\sin a\pi}{\cos 4a\pi}\cos(a\pi\sin\phi)a\pi\cos\phi \quad . \quad . \quad (11.2)$$

By a detailed analysis of this formula it can be shown that a large frame, in particular the square frame with half-wavelength sides, may be expected to give a much greater sharpness of minimum than a small frame. It is realized, however, that sharpness of minimum, though important, is not the only or even the most important feature of a direction-finding system. Nevertheless, the large frame would seem to be worth considering in relation to this application.

(12) OPTIMUM SHAPE OF RECTANGULAR FRAME WITH BALANCED TUNING

For a given total length, the effective e.m.f. depends on the shape of the frame, in virtue of the terms

$$\sinh\frac{Ph}{2}\sin\frac{2\pi}{\lambda}b \quad . \quad . \quad . \quad . \quad (12.1)$$

Putting $$b = \tfrac{1}{4}l - \tfrac{1}{2}h \quad . \quad . \quad . \quad . \quad (12.2)$$

and neglecting the attenuation component of P, these terms become

$$\sin\frac{2\pi}{\lambda}\cdot\frac{h}{2}\sin\frac{2\pi}{\lambda}(\tfrac{1}{4}l - \tfrac{1}{2}h) \quad . \quad . \quad (12.3)$$

i.e. $$\cos\frac{2\pi}{\lambda}(h - \tfrac{1}{4}l) - \cos\frac{2\pi}{\lambda}\cdot\frac{l}{4} \quad . \quad . \quad (12.4)$$

The critical values of h are therefore those for which

$$\sin\frac{2\pi}{\lambda}(h - \tfrac{1}{4}l) = 0 \quad . \quad . \quad . \quad (12.5)$$

i.e. $$\frac{2\pi}{\lambda}(h - \tfrac{1}{4}l) = n\pi; \quad n = 0, 1, 2, 3, \text{etc.} \quad . \quad (12.6)$$

or $$h = \tfrac{1}{4}l + \tfrac{1}{2}n\lambda \quad . \quad . \quad . \quad . \quad . \quad (12.7)$$

and $$2b = \tfrac{1}{4}l - \tfrac{1}{2}n\lambda \quad . \quad . \quad . \quad . \quad . \quad (12.8)$$

Of these, the only case of practical importance is the square shape

$$2b = h = \tfrac{1}{4}l \quad . \quad . \quad . \quad . \quad (12.9)$$

The author has endeavoured to compare these conclusions with regard to optimum shape with those arrived at by L. S. Palmer in his work on rectangular frame aerials.* Comparison is made difficult by the fact that Prof. Palmer's results are stated throughout in terms of current and the observations recorded are in terms of a current flowing, not in the loop itself, but in a kind of tuning circuit formed, apparently, by connecting a tuning condenser across a short length of the conductor of the loop. This branch circuit can be regarded as constituting a kind of tuning circuit, but it is not certain that its range of variation was sufficient for producing a true tuned condition over the whole range of frame dimensions examined.

In Fig. 6 of the paper referred to, a large number of current maxima are recorded, as functions of width for various heights, the wavelength being stated as 8·65 m. For one set of maxima the total lengths are approximately 15·6, 16, 16·4, 17·6, and 18 m. These are all in the neighbourhood of 2λ and these maxima are in accordance with paragraph 6 of Section (10). The maximum-maximum for l = approximately 2λ seems to occur for h just less than $\tfrac{1}{2}\lambda$, as compared with $\tfrac{1}{2}\lambda$ on the present theory. Other current maxima occur, however, with l = 24·8, 24·3, 23·4, 24·4, which are in the neighbourhood of, though less than, $l = 3\lambda$. On the present theory the effective impedance is certainly a minimum under these conditions, but the effective e.m.f. is also very small, and current maxima would not be expected. The difference may arise from tilt of the field in Palmer's experiments. Minima are recorded for total lengths in the neighbourhood of λ and $5\lambda/2$, which is also to be anticipated from the present theory. Thus some at least of the conclusions of the present theory are borne out by Prof. Palmer's observations, to a degree of accuracy as good as could be expected in view of the simplifying assumptions of the theory, namely that the effects of mutual interactions of the different parts of the aerial are adequately represented by the basic differential equations.

(13) ASYMMETRY AS A FUNCTION OF SIZE AND SHAPE

For most practical purposes it is desirable that the asymmetrical current i_g shall be as small as possible. One general method of achieving this is to separate the neutral point from earth by as high an impedance as possible, and to keep to a minimum the e.m.f.'s induced anywhere except in the frame aerial itself. It will, however, be of interest to examine the dependence of i_g on the size and shape of the frame aerial.

In the first place, that part of the asymmetrical e.m.f. which depends only on the frame and not on the neutral point connections to earth contains the term $\cos 2\pi b/\lambda$, and therefore vanishes whenever $2b = \tfrac{1}{2}\lambda$ or any integral multiple of this. It becomes small when $h = \lambda$, but this is not a practical case as the symmetrical e.m.f. is also small for this condition. It becomes large when $l = \lambda$, a condition which has already been discarded on other grounds.

A suggestion of some practical interest is the connection of the neutral point to earth by a half-wavelength or a wavelength line. In this case the e.m.f. due to the earth lead reduces to $\alpha\lambda^2/(4\pi)$ or $\alpha\lambda^2/(2\pi)$ and is therefore very small. At the same time the corresponding term in the impedance becomes very small, but if in addition $l = 2\lambda$, the term $\tfrac{1}{2}Z \coth \tfrac{1}{2}Pl$ in the impedance to i_g becomes very large. Thus the condition $2b = h = \tfrac{1}{2}\lambda$ and $g = \lambda$ or $\tfrac{1}{2}\lambda$ appears to have every advantage, since it minimizes both components of the unsymmetrical e.m.f. and opposes a high impedance to the residue.

* See Reference (3).

(14) RECTANGULAR FRAME AERIAL: UNBALANCED TUNING

The equations for the currents i_0 and i_g for a frame as in Fig. 2, but with the left-hand tuning condenser replaced by a short-circuit, can be derived from (4.12) and (4.13) by putting $Z_3 = 0$, i.e. $\coth Pa_3 = 0$, and by summation of the e.m.f.'s acting on the vertical sides, as in Section (6). This process gives

$$i_0(Z_0 + Z\tanh Pl) = \frac{2_e}{P}\cdot\frac{\sinh(\tfrac{1}{2}Ph)}{\cosh Pl}$$
$$\left\{\epsilon^{-j\theta}\cosh\frac{3Pl}{4} - \epsilon^{j\theta}\cosh\frac{Pl}{4}\right\} + 2v_g\frac{\sinh^2(\tfrac{1}{2}Pl)}{\cosh Pl} \quad . \quad (14.1)$$

and

$$i_g(Z_0 + Z\tanh Pl) = \frac{2e}{P}\cdot\frac{\sinh\tfrac{1}{2}Ph}{\cosh Pl}$$
$$\left\{4\sinh(\tfrac{1}{2}Pl)\sinh(\tfrac{1}{4}Pl)\cos\theta\right\}$$
$$+ Z_0\left[\epsilon^{j\theta}\sinh(\tfrac{3}{4}Pl) - \epsilon^{-j\theta}\sinh(\tfrac{1}{4}Pl)\right]$$
$$+ v_g\left\{\frac{Z_0}{Z}\tanh Pl + 4\frac{\sinh^2(\tfrac{1}{2}Pl)}{\cosh Pl}\right\} \quad . \quad . \quad (14.2)$$

where $\theta = 2\pi b/\lambda$.

The formulae are complicated and the system appears to be, in general, ill adapted for either field-strength measurement or direction-finding, and it is not therefore proposed to analyse these formulae at any length. Some general observations may, however, be made.

So far as direction-finding is concerned, we have the well-known result that the received signal is not zero when the frame is parallel to the wave-front, i.e., putting $\theta = 0$,

$$i_0(Z_0 + Z\tanh Pl) = \frac{2e}{P}\frac{\sinh(\tfrac{1}{2}Ph)\sinh(\tfrac{1}{2}Pl)\sinh(\tfrac{1}{4}Pl)}{\cosh Pl}$$
$$+ 2v_g\frac{\sinh^2(\tfrac{1}{2}Pl)}{\cosh Pl} \quad . \quad . \quad . \quad (14.3)$$

This is the familiar "antenna effect." It may, however, be pointed out that the effect becomes very small when $l = 2\lambda$, a condition which also gives a large maximum value. Thus a frame with $2b = h = \tfrac{1}{2}\lambda$, earthed by a

vertical line of length λ or $\frac{1}{2}\lambda$, might be worth considering for direction-finding on a fixed wavelength. In fact, such a frame has characteristics similar to those for the corresponding case with symmetrical tuning, which obviously arises from the fact that the effective impedance becomes very small in both cases and the required tuning impedance Z_0 correspondingly small.

(15) CIRCULAR LOOP: BALANCED TUNING

The formulae can be derived from (5.2) and (5.3) by a process of integration. Referring to Fig. 5, the field is assumed vertical and of zero phase at the vertical diameter. The tangential components of the fields at P and P′ will be $e \sin \phi$ and $-e \sin \phi$ respectively, and the phases $-\theta$ and θ respectively, where $\theta = 2\pi r \sin \phi/\lambda$. From (5.2) and (5.3), the element di of i due to the summation for the two elements $rd\phi$ at P and P′ will be

$$di \frac{\cosh P(a_0 + \frac{1}{2}l)}{\sinh Pa_0}$$

$$= -j\frac{e}{Z}r \sin \phi \cosh Pr(\pi - \phi) \sin \left(\frac{2\pi r}{\lambda} \sin \phi\right) d\phi \quad (15.01)$$

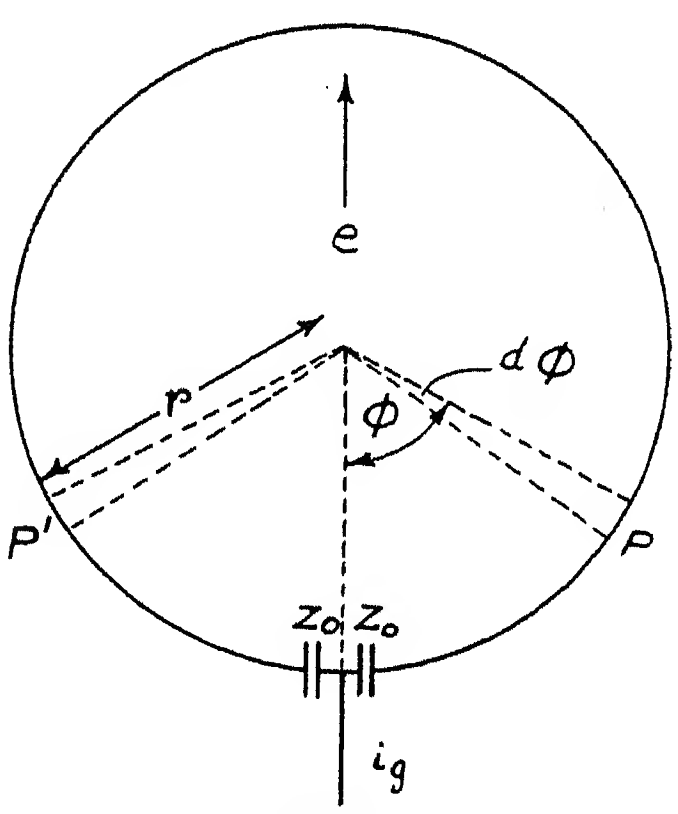

Fig. 5

Therefore

$$i \frac{\cosh P(a_0 + \frac{1}{2}l)}{\sinh Pa_0}$$

$$= -j\frac{e}{Z}r \int_0^\pi \sin \phi \cosh Pr(\pi - \phi) \sin \left(\frac{2\pi r}{\lambda} \sin \phi\right) d\phi \quad . \quad (15.02)$$

For the general case when $2\pi r/\lambda$ is not an integer, it will be a close approximation to put

$$\cosh Pr(\pi - \phi) \simeq \cos \frac{2\pi r}{\lambda}(\pi - \phi) \quad . \quad (15.03)$$

i.e. $$i \frac{\cosh P(a_0 + \frac{1}{2}l)}{\sinh Pa_0}$$

$$= -j\frac{e}{Z}r \int_0^\pi \sin \phi \cos \frac{2\pi r}{\lambda}(\pi - \phi) \sin \left(\frac{2\pi r}{\lambda} \sin \phi\right) d\phi$$

$$= -j\frac{e}{Z}r \int_0^\pi \sin \phi \cos \frac{2\pi r \phi}{\lambda} \sin \left(\frac{2\pi r}{\lambda} \sin \phi\right) d\phi \quad . \quad (15.04)$$

The integration can be carried out, for all cases in which $2\pi r/\lambda$ is not an integer, by means of the well-known formula

$$\sin (n \sin \phi) = 2 \sum J_p(n) \sin p\phi;\ p = 1, 3, 5, \text{etc.} \quad . \quad . \quad (15.05)$$

and the result is

$$i \frac{\cosh PC\, a_0 + \frac{1}{2}l}{\sinh Pa_0}$$

$$= j\frac{e}{Z} \sum \frac{-4\, pn \sin n\pi}{\{(p + 1)^2 - n^2\}\{(p - 1)^2 - n^2\}};\ p = 1, 3, 5, \text{etc.} \quad . \quad . \quad (15.06)$$

where $$n = 2\pi r/\lambda \quad . \quad . \quad . \quad . \quad (15.07)$$

Thus the effective induced e.m.f. is given by

$$e_e = -8jnr \tan n\pi \,.\, e \,.\, \sum \frac{pJ_p(n)}{\{(p+1)^2 - n^2\}\{(p-1)^2 - n^2\}} \quad . \quad . \quad (15.08)$$

As a confirmation, it may be noted that for small values of n this tends to the usual value given in (1.1), i.e. the limit of the summation when $n \to 0$ is $-\frac{1}{8}n$.

Therefore $$|e_e| \to 8nrn\pi \frac{e}{8n} = n\pi re$$

$$= \frac{2\pi}{\lambda} Ae \quad . \quad . \quad . \quad (15.09)$$

where $A = \pi r^2$ = area of loop.

If for any reason the more exact formula is required, i.e. a formula which includes the small effect of the resistance terms on the induced e.m.f., then since

$$\cosh Pr\phi = \cos (n - j\alpha r)\phi \quad . \quad . \quad (15.10)$$

the more exact formula can be derived by substituting $(n - j\alpha r)$ for n in the above, except in $J_p(n)$, which is not affected.

Certain special cases will be of interest. Deriving the formula for e_e from (15.02) (as in Section 7) gives

$$e_e = \frac{2jre}{\cosh Pr\pi} \int_0^\pi \cosh Pr\phi \sin \phi \sin (n \sin \phi) d\phi \quad (15.11)$$

$$\simeq \frac{2jre}{\cos n\pi} \int_0^\pi \cos n\phi \sin \phi \sin (n \sin \phi) d\phi \quad . \quad (15.12)$$

(1) $l = \lambda$; i.e. $n = 1$.

$$e_e = -2jre \cdot \frac{1}{2} \int_0^\pi \sin 2\phi \sin (\sin \phi) d\phi = 0 \quad (15.13)$$

In practice e_e will not be zero but will have a very small value depending on the resistance term α. It may be noted that for a rectangular loop with $l = \lambda$, e_e was also very small.

(2) $l = 2\lambda$; i.e. $n = 2$.

$$e_e = 2jre \int_0^\pi \cos 2\phi \sin \phi \sin (2 \sin \phi) d\phi \quad (15.14)$$

$$= 2jre\frac{\pi}{2}\{J_3(2) - J_1(2)\} \quad . \quad . \quad . \quad . \quad (15.15)$$

$$= j \times 0{\cdot}448\lambda e \quad . \quad . \quad . \quad . \quad . \quad . \quad (15.16)$$

This may be compared with the formula already determined in Section (6) for a square coil with $l = 2\lambda$, i.e.

$$e_e = j\frac{2}{\pi}\lambda e = j \times 0\cdot 637\lambda e$$

Finally, in Section (10), it was shown that for a square frame with symmetrical tuning, the total length of conductor being $\frac{1}{4}\lambda$, the effective e.m.f. would be about 23 % greater than that calculated by the simple formula. By formula (15.08) the same ratio can be calculated for the circular loop of the same total length. It is found that for $n = \frac{1}{4}$ only the first term of the series is significant, and equals $0\cdot 504$ (i.e. approximately $\frac{1}{8}n$), and the e.m.f. in this case is about 28 % greater than that given by the simple formula. Thus changing the shape from square to circular only changes the effective e.m.f. by about 5 %.

(16) A NOTE ON THE MEASUREMENT OF THE OUTPUT VOLTAGE

It was shown in Section (6) that the currents i_0 and i_3 through the equal tuning impedances on either side of the mid or "earth" point on a symmetrically tuned frame aerial can be put in the form

$$i_0 = i + \tfrac{1}{2}i_g$$
$$i_3 = i - \tfrac{1}{2}i_g$$

The term i_g depends on the nature of the earth connection, if any, and in any case on the impedance to earth of any apparatus connected to the mid-point. Thus, for field-strength measurement, unless the current i_g can be made negligibly small it is in general necessary to be able to measure the vector sum of the unequal voltages produced across the two halves of the tuning impedance in series.

Various means of doing this suggest themselves. For example, the voltages can be applied to the grids of a push-bell amplifying circuit of which the output is a single voltage proportional to the vector sum of the input voltages. Such an arrangement, however, though easy to design in principle, is not easy to realize in practice, particularly to the shorter wavelengths to which most of the considerations in this analysis apply. Further, it must be pointed out that the direct application of the voltages to the terminals of a "push-pull" rectifier circuit will not in general give an output proportional to the vector sum of the input voltages.

It can, however, be shown on theoretical grounds that a push-pull frequency-change system may satisfy the necessary condition, provided that a close approximation to electrical symmetry in the two halves of the system can be realized. Similarly the multi-grid frequency-change valves in which the frequency-change mechanism is essentially the multiplication of a signal voltage and a local oscillator voltage, will, under the same assumed conditions, give an output proportional to the vector sum of the input voltages. In both cases, however, considerable care will be necessary to realize the assumed conditions.

(17) CONCLUSIONS

On the assumption that the current and voltage relationships for a single conductor bent into a closed shape—rectangle or circle—can be represented by the partial differential equations of transmission-line theory, formulae have been developed for the effective induced e.m.f. and effective aerial impedance of such closed aerials, without limitation of linear dimension. Subject to experimental confirmation, the work is considered to serve two main objects. (1) It should enable some estimate to be made of the size at which a frame aerial, as used for field-set strength measurement, ceases to be "small" in the generally accepted sense, and it should also enable the e.m.f. induced in such a "small" frame to be calculated, in terms of the field intensity, somewhat more accurately than by the usual simple formula. (2) It should serve as a preliminary guide in deciding on the type of aerial best suited to field-strength measurement at short and ultra-short wavelengths.

In the only existing internationally agreed recommendation on the latter subject (Commission I, U.R.S.I., 1934), the loop aerial is made the standard "collector" for field-strength measurement for wavelengths longer than 15 m., and "a di-pole capable of orientation" for all other wavelengths. It may be, however, that a loop aerial, of dimensions not necessarily small compared with the wavelength, would prove to have advantages. This is essentially a matter for practical experience, and the present theoretical analysis may serve as a guide for such experiments.

Certain other points have emerged from the analysis. It has been shown, for example, that a loop receiving system having complete geometrical symmetry will not necessarily show electrical symmetry in its "maximum" orientation even in a uniform wave-field; i.e. the currents and voltages will not, in general, be symmetrical about the vertical axis of geometric symmetry. This is true in general even for small loop aerials, but will not in general be of practical significance in such cases. It is, however, a feature which calls for some care in short-wave and ultra-short-wave intensity measurements.

This asymmetry is of course already familiar in the use of coil aerials for direction-finding. The formulae give the magnitude of the "antenna effect" in any given case and confirm, moreover, that the establishment of geometrical and electric-circuit symmetry should suffice to eliminate the effect in the "minimum" orientation of the loop aerial.

(18) ACKNOWLEDGMENTS

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REFERENCES

(1) F. M. Colebrook: "An Experimental and Analytical Investigation of Earthed Receiving Aerials," *Journal I.E.E.*, 1932, vol. 71, p. 235.
(2) J. C. Brainerd: "Inductance at High Frequencies," *Proceedings of the Institute of Radio Engineers*, 1934, vol. 22, p. 395.
(3) L. S. Palmer: "On the Action of Tuned Rectangular Frame Aerials when receiving Short Waves," *Proceedings of the Royal Society*, 1932, vol. 136, p. 193.

THE DISTRIBUTION OF ULTRA-HIGH-FREQUENCY CURRENTS IN LONG TRANSMITTING AND RECEIVING ANTENNAE*

By Professor L. S. PALMER, D.Sc., Ph.D., Member, and K. G. GILLARD, B.Sc.

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SUMMARY

The distribution of ultra-high-frequency currents in long transmitting and receiving antennae is considered analytically, and experiments are described which were undertaken to test the conclusions arising from the theoretical analyses.

With an isolated transmitting antenna energized at any point, the current is found to be distributed sinusoidally in the two parts of the antenna which are separated by the point of energy input. The currents in the two parts are dependent upon each other in a manner determined by the approximate equations (3) and (4) in the paper.

With an isolated receiving antenna energized by a uniform electromagnetic field, it is found that the current distribution is such that current nodes occur at intervals of one wavelength measured from both ends of the aerial. The distribution is given approximately by equation (5) in the paper.

" End effects " and modifications produced by the experimental methods used are also discussed.

(1) INTRODUCTION

In order to determine the radiating and receiving properties of a long antenna, it is necessary to know the current distribution along the antenna wire when it is used as a transmitting aerial and as a receiving aerial, respectively. This, in turn, presupposes a knowledge of the variation along the antenna of its impedance per unit length: a complex quantity which is not susceptible to any simple mathematical treatment.

Any exact theory must take into account such interrelated factors as the difference between the wave velocity along the antenna wire and in the surrounding medium due to the distributed electrical properties of the particular wire, the phase change on reflection of the waves due to localized electrical properties near the ends of the wire, the so-called " shortening factor " due, according to some authorities, to both distributed and localized effects, the possible reflection of the waves from the earth's surface, and other similar items all of which tend to make any exact theory extremely complicated. Various authors have considered one or more of these factors and, by suitable approximations, have evolved theories which, in the few cases where they have been tested, conform approximately to experimental data. When, however, experimental measurements at very high frequencies are attempted, the inherent difficulties arising from the use of ultra-short waves with long antennae introduce errors which are much greater than those arising from the usual theoretical approximations. For example, the introduction into an antenna of a current-measuring instrument produces effects at very high frequencies which considerably alter the current distribution anticipated by any of the published theories. In fact, it is not possible, in many cases, to decide experimentally between, for example, the simple theory of the current distribution in earthed receiving antennae with uniform electrical constants put forward by Moullin† in 1925, or, say, the more elaborate theories of Metzler‡ and Hara,§ the former of whom in 1936 used transmission-line equations and resolved his resultant current into progressive and stationary waves, and the latter of whom (in the same year) calculated the radiation impedance of linear conductors assuming a sinusoidal current distribution. Again, Colebrook|| in 1932 used transmission-line equations and gave three different values to the antenna electrical constants per unit length for three different parts of the antenna, and then considered special cases of his general formula; whilst Labus,¶ in the following year, determined the aerial impedance from the line integral $\int E(x)I(x)dx$, where $I(x)$ is the current produced by the x component of the incident field E acting on an aerial with uniformly distributed electrical constants.

In no instance have the theoretical conclusions concerning current distributions in long transmitting or receiving aerials been tested experimentally at high frequencies, although in 1928 Wilmotte** measured the current distribution in the particular case of an earthed transmitting aerial which was 11 m. long and radiated waves as short as 15·6 m.

It was therefore felt desirable to attempt to reduce experimental errors as much as possible, and then to employ the simplest theory consistent with the fact that the errors arising from the theoretical assumptions should not exceed those arising from the experimental methods adopted. The following simple theoretical treatment complied with this limitation, and in Section (4) the results of experiments on wavelengths of about 70 cm. are compared with the theoretical deductions.

With greater precision in the future it is hoped to be able to verify experimentally some of the more rigorous theoretical expressions which have been deduced by other authors, but this was not possible with the methods and apparatus at present available.

(2) THEORETICAL CONSIDERATIONS

The essential distinction between long transmitting and long receiving antennae when used with ultra-short waves depends on the fact that in the former case the input e.m.f. is concentrated over a short length of

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† See Reference (1). ‡ *Ibid.*, (2). § *Ibid.*, (3). || *Ibid.*, (4). ¶ *Ibid.*, (5). ** *Ibid.*, (6).

the antenna wire, whilst in the latter case it is usually uniformly distributed throughout the whole length of the wire. These two particular cases will now be considered with a view to determining the approximate current distributions which result.

(A) The Long Transmitting Antenna

Consider an isolated antenna AB (Fig. 1) of length greater than one wavelength, and let it be energized at any point P which is at a distance D from the lower end B.

As it is intended to simplify the theoretical treatment as much as possible owing to the unavoidably large errors inherent in ultra-high-frequency measurements, it will be assumed that the electric constants of the antenna wire are uniform throughout its length and that the resistance and leakance are negligible compared with the inductive and capacitive reactances respectively.

Then if L and C denote the inductance and capacitance per unit length of the antenna wire, the fundamental equations for the voltage V and current I at any arbitrary point Q are given by

$$-dV = j\omega LIdx \quad \text{and} \quad -dI = j\omega CVdx$$

where $j = \sqrt{(-1)}$ and ω is 2π times the frequency.

Thus $d^2V/dx^2 = -\omega^2 LCV$ and $d^2I/dx^2 = -\omega^2 LCI$.

Hence $I = S\cos 2\pi x/\lambda + T\sin 2\pi x/\lambda$

where λ is the wavelength and S and T are the integration constants. These can be determined from the particular boundary conditions at A, B, and P. Let the current in the portion AP be I_A and that in the portion PB be I_B. Then these conditions are:—

(i) At A, $x = l$ and $I_A = 0$.
(ii) At B, $x = 0$ and $I_B = 0$.
(iii) At P, $x = D$ and $I_A = I_B = I_0 e^{j\omega t}$ (say).
(iv) At P, $x = D$ and $z_0 \Delta(dI/dx) = E_0 e^{j\omega t}$,

where z_0 is some constant. This follows from the fact that any change in the current gradient at P must be compensated by a voltage input $E_0 e^{j\omega t}$. Thus the fourth boundary condition may be written

$$E_0 e^{j\omega t} = z_0\left(\frac{dI_A}{dx} - \frac{dI_B}{dx}\right)$$

It will be necessary, in view of this current change at P, to treat separately the current in those parts of the antenna above and below P.

From boundary conditions (ii) and (iii), we have

$$S = 0 \quad \text{and} \quad T = I_0 e^{j\omega t}/\sin 2\pi D/\lambda$$

Hence
$$I_A = \frac{\sin 2\pi(l-x)/\lambda}{\sin 2\pi(l-D)/\lambda} I_0 e^{j\omega t} \quad . \quad . \quad . \quad (1)$$

and
$$I_B = \frac{\sin 2\pi x/\lambda}{\sin 2\pi D/\lambda} I_0 e^{j\omega t} \quad . \quad . \quad . \quad . \quad (2)$$

That is, if the boundary conditions (i), (ii), and (iii), are alone considered, the currents I_A and I_B should vary sinusoidally and independently along the two parts of the antenna with zero current at the open ends remote from the input e.m.f. at P. The present problem is, however, more complicated because the e.m.f. at P, unlike an e.m.f. localized at the foot of an aerial, does not alone prescribe the motions of the charges in each portion of the antenna. For example, the current I_A is not only dependent on the e.m.f. at P but is also affected by the current I_B in the portion of the antenna PB. As a consequence of this we must employ the boundary condition (iv), which gives the relation between the change of current gradient at P and the input e.m.f., and so determines a relation between E_0 and I_0.

On differentiating equations (1) and (2) with respect to x, and using condition (iv), we get the required relation between E_0 and I_0, namely

$$I_0 = \frac{\lambda E_0}{2\pi z_0} \cdot \frac{(\sin 2\pi D/\lambda)\sin 2\pi(l-D)/\lambda}{\sin 2\pi l/\lambda}$$

Hence

$$I_A = \frac{\lambda}{2\pi} \cdot \frac{E_0}{z_0}\left[\frac{\sin 2\pi D/\lambda}{\sin 2\pi l/\lambda}\sin\frac{2\pi(l-x)}{\lambda}\right]\sin(\omega t + \pi) \quad (3)$$

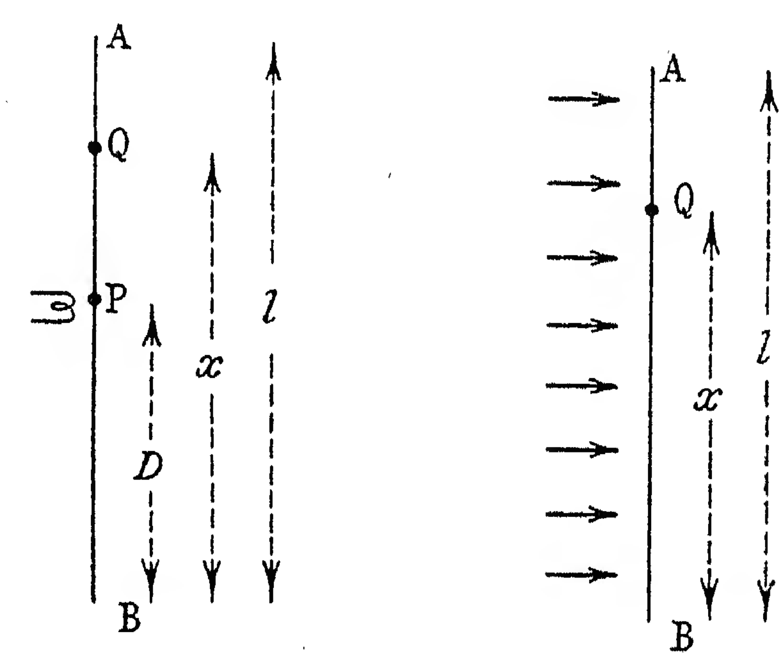

Fig. 1 Fig. 2

and

$$I_B = \frac{\lambda}{2\pi} \cdot \frac{E_0}{z_0}\left[\frac{\sin 2\pi(l-D)/\lambda}{\sin 2\pi l/\lambda}\sin\frac{2\pi x}{\lambda}\right]\sin(\omega t + \pi) \quad (4)$$

From these two equations three conclusions immediately follow:—

(a) Firstly, the current in each portion of the antenna varies sinusoidally and is zero at the open ends remote from the e.m.f. at P. This conclusion has already been deduced and tested by Wilmotte* for the particular case when P coincides with the point B (Fig. 1), and by Metzler† when P is mid-way between A and B.

(b) Secondly, it follows from equations (3) and (4) that the two currents I_A and I_B are not independent of each other. If the length of one portion of the antenna be an integral number of half-wavelengths (say AP $= n\lambda/2$), then the current I_B in the other portion PB becomes zero for all values of x, whatever its length (except in the special case where PB is also an integral number of half-waves in length). Similarly, when PB (or D) $= n\lambda/2$, $I_A = 0$ throughout the length AP (except when AP also equals $n\lambda/2$).

Owing to the fact that in any given antenna the phase-change on reflection from the open ends of the

* See Reference (6).

† *Ibid.*, (2).

aerial wire will not be exactly π, the current will not be zero when $x = 0$ or l, and consequently the current I_A, for example, will attain a minimum value for lengths PB or D which will be somewhat less than $n\lambda/2$. Furthermore the finite values of the antenna resistance and leakance will affect the magnitude of the currents in such a way that the maximum values will be reduced and the minimum values will not be zero.

Again, when the length of one portion (PB say) of the antenna is an odd number of $\frac{1}{4}$-wavelengths, the current I_A in the other part will be a maximum. That is, if $D = (2n + 1)\lambda/4$, I_A will be a maximum, or if $(l - D) = (2n + 1)\lambda/4$, I_B will be a maximum. As before, these critical values will be slightly modified because the phase-change on reflection is not exactly π, and the antenna resistance and leakance are not quite negligible.

Metzler* has treated this problem of the long transmitting antenna from a somewhat different standpoint and has studied the effects of resistance and leakance by analysing his expression for the antenna current into progressive and stationary waves; the former determine the slight modifications produced on the simple stationary-wave system due to currents passing through the nodal points in order to compensate for resistance and leakance losses in the antenna.

(*c*) A third conclusion follows if in equation (3) I is a function of l, and D and $(l - x)$ are kept constant. Then $I_A \propto \operatorname{cosec} 2\pi l/\lambda$. That is, if the point Q at which I_A is measured is at a constant distance from the end A, and the point P where the e.m.f. is applied is at a constant distance from the end B, then the current measured at Q should be proportional to $\operatorname{cosec} 2\pi l/\lambda$.

Thus by three different experimental methods based on the above three conclusions it should be possible to check the foregoing theoretical equations (3) and (4). Such experiments are described in Section (3), and the results are discussed in Section (4).

(B) The Long Receiving Antenna

Consider a long isolated receiving antenna AB energized throughout its length by a uniform e.m.f. $E_0 e^{j\omega t}$ per unit length. With the same assumptions and nomenclature as before, the fundamental equations for the voltage V and current I at any arbitrary point Q will now be

$$-dV = j\omega LIdx - E_0 e^{j\omega t}dx$$

and
$$-dI = j\omega CVdx$$

Thus
$$\frac{d^2V}{dx^2} = -\omega^2 LCV \text{ as before, but}$$

$$\frac{d^2I}{dx^2} = -\omega^2 LCI - j\omega CE_0 e^{j\omega t}$$

Hence
$$V = S' \cos 2\pi x/\lambda + T' \sin 2\pi x/\lambda$$

and
$$I = \frac{E_0}{\omega L}e^{j\omega t} + S'\sqrt{\left(\frac{C}{L}\right)} \sin 2\pi x/\lambda + T'\sqrt{\left(\frac{C}{L}\right)} \cos 2\pi x/\lambda$$

S' and T' are the integration constants to be determined from the particular boundary conditions, which are, in this case,

(i) at A: $x = l$ and $I = 0$.
(ii) at B: $x = 0$ and $I = 0$.

Hence from (ii) $$T' = -\frac{\lambda E_0}{2\pi}e^{j\omega t}$$

and from (i) $$S' = -\frac{\lambda E_0}{2\pi}e^{j\omega t} . \tan \pi l/\lambda$$

Thus

$$I = \frac{2E_0}{\omega L}\sin\frac{\pi x}{\lambda}\left(\sin\frac{\pi x}{\lambda} - \tan\frac{\pi l}{\lambda}\cos\frac{\pi x}{\lambda}\right)\cos\omega t$$

$$= \frac{2E_0}{\omega L}\left[\sec\frac{\pi l}{\lambda}\sin\frac{\pi x}{\lambda}\sin\frac{\pi(l - x)}{\lambda}\right]\cos(\omega t + \pi) \quad . \quad (5)$$

From this equation it follows that the current is not distributed sinusoidally with current nodes every $\frac{1}{2}$-wavelength, but that current nodes occur at intervals of a whole wavelength measured from both ends of the antenna. Looked at geometrically rather than physically, the current distribution may be considered to be represented by a sine wave with its axis parallel to but displaced from the antenna wire. This fact was first pointed out by Hagen and recorded by Korshenewsky.* Colebrook refers to it in the last section of a recent paper in the *Journal*.† The resulting theoretical current distributions for different values of l/λ are shown by the seven dotted graphs of Fig. 9.

The result given in equation (5) for the current at any point Q (Fig. 2) may also be obtained by integrating over the length l of the antenna the effect at Q of a current $I_0 dl$ at any other point P, with the assumptions that waves travel from P with the velocity $1/\sqrt{(LC)}$ in both directions and are reflected to and fro an infinite number of times along the antenna without loss of amplitude and with phase-change of π at the open ends of the antenna.

It was found that the simple theoretical result given by equation (5) could not be verified by direct experiment, firstly because the currents were not zero at the open ends of the antenna, or in other words, the phase-change on reflection of the waves from the ends of the antenna differed from π; and secondly, because the introduction of the current-measuring instrument appreciably modified the original current distribution. It is a comparatively simple matter to modify equation (5) by taking into consideration the fact that the phase-change on reflection is not exactly π. The error is that which would be produced if the aerial were extended by an amount $a/2$, say, at each end. The phase-change at the actual termination of the wire would be $2\left(\frac{2\pi}{\lambda}\cdot\frac{a}{2}\right)$ or $2\pi a/\lambda$, and the appropriate boundary conditions are that the current is zero for values of x equal to $-\frac{1}{2}a$ and $(l + \frac{1}{2}a)$. With these conditions the current amplitude at any point Q is given by

$$I_0 = K\left[1 - \sec\frac{\pi(l + a)}{\lambda}\cos\frac{\pi a}{\lambda}\cos\frac{\pi(l - 2x)}{\lambda}\right] \quad (6)$$

where K is a constant. This expression reduces to the

* See Reference (2).

* See Reference (7).

† *Ibid.*, (4).

amplitude of the current given by equation (5) when $a \to 0$.

Although equation (6) should be more exact than equation (5) for the current distribution, it is not possible to check it practically because of the instrumental error referred to above.

It was found experimentally that the introduction of a vacuum thermojunction into the antenna shortened its effective length by an amount $2b$, say. That is, the thermojunction acted as a length $2b$ of antenna wire through which the current circulated but along which the e.m.f. of the incident field was inoperative. Consequently, for the ends of this section of the antenna the appropriate boundary conditions are the continuity of current and current gradient and the discontinuity of e.m.f. If the thermojunction be inserted at the point Q (Fig. 2) and the "equivalent length" of the antenna be l' $(= l + 2b)$, then the necessary 12 boundary conditions are (at distances x' along the antenna):—

At B, where $x' = -\frac{1}{2}a$, $I_1 = 0$; $E_1 = E$.

At Q $\begin{cases} \text{where } x' = (x - b),\ I_1 = I_2,\ I_1' = I_2';\ E_1 = E, \\ \quad E_2 = 0. \\ \text{where } x' = (x + b),\ I_2 = I_3,\ I_2' = I_3';\ E_2 = 0, \\ \quad E_3 = E. \end{cases}$

At A, where $x' = (l + \frac{1}{2}a)$, $I_3 = 0$; $E_3 = E$.

The currents will differ in phase by the appropriate values of $2\pi x'/\lambda$, but will have constant amplitude, the resistance and leakage being neglected.

The resulting equation for the amplitude of the current at Q is

$$\begin{aligned} I_0 = K \operatorname{cosec} 2\pi(l' + a)/\lambda \big[&\sin 2\pi(l' + a - b)/\lambda \\ &+ \sin 2\pi b/\lambda \,.\, \cos 2\pi(l' - 2x)/\lambda \\ &- 2 \cos \pi a/\lambda \,.\, \sin \pi(l' + a)/\lambda \,.\, \cos \pi(l' - 2x)/\lambda \big] \end{aligned} \quad (7)$$

The expression on the right-hand side reduces to the amplitude in equation (5) when $a = b = 0$ and $l' = l$.

Equation (7) may also be deduced by the alternative method of summing the infinite series of waves which may be considered to travel to and fro along the antenna after reflection at the ends.

The graphical representations of equation (7) are given by the seven full-line curves in Fig. 9, and may there be compared with the dotted graphs of equation (5).

(3) EXPERIMENTAL WORK

In order to test the foregoing theoretical conclusions it was decided to work with as short waves as possible so as to keep the dimensions of the apparatus as small as possible. Furthermore, the antennae could then be elevated several wavelengths above the earth's surface without any serious experimental difficulty.

A valve oscillator was constructed to work on wavelengths of the order of 60 to 100 cm. When testing the validity of equations (3) and (4), the oscillator was coupled indirectly to a straight brass-rod antenna of variable length, and when used in connection with the measurement of current distributions in receiving antennae [equations (5), (6), and (7)] it was coupled to an ordinary half-wave radiator with a cylindrical parabolic reflector. With these experiments the brass rod was used as the receiving antenna.

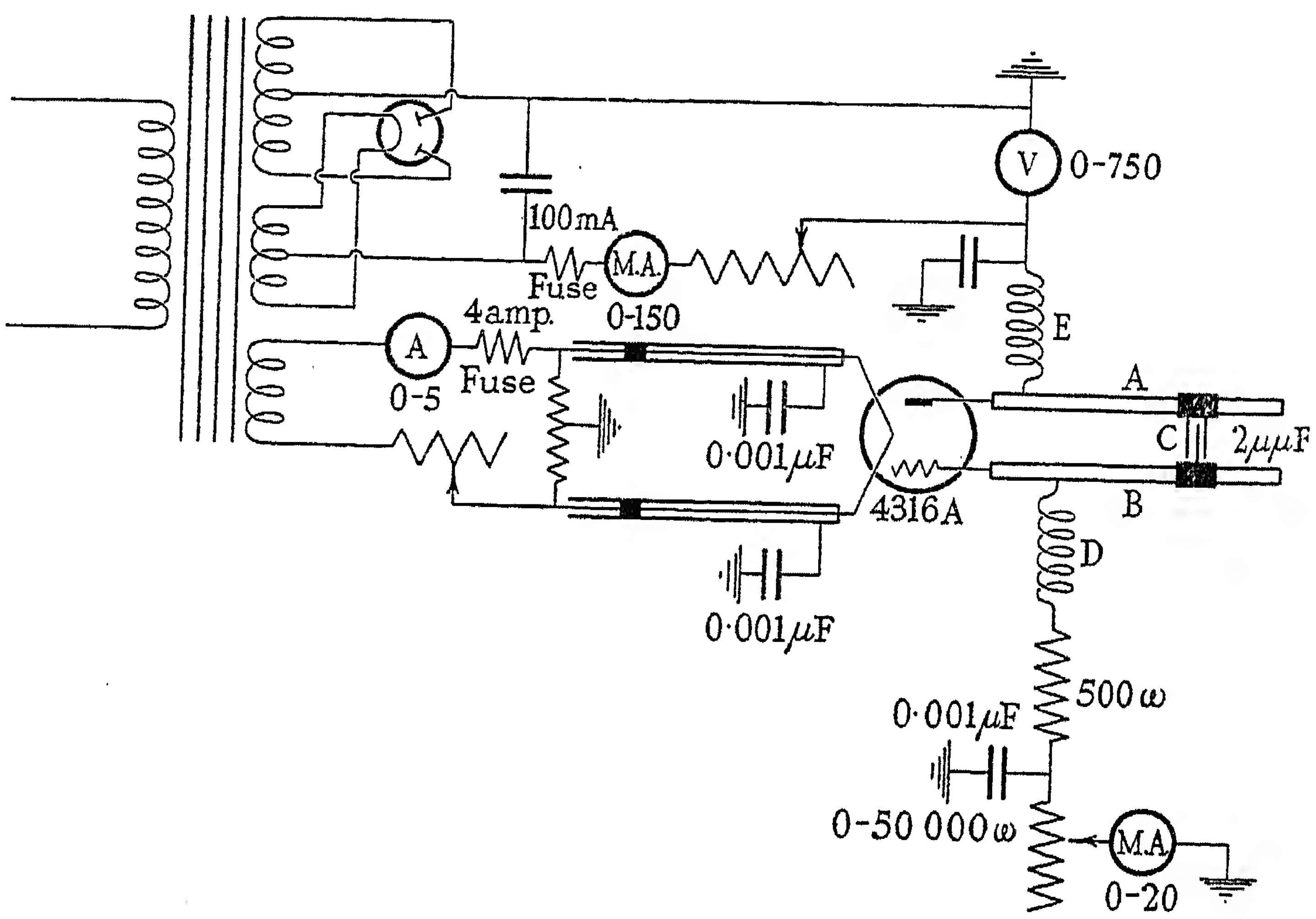

Fig. 3

(A) The Oscillator

A G.E.C. 4316A valve was used with the modified Hartley circuit shown in Fig. 3. To the plate and grid were fastened two straight rods A and B, which were connected together by a small fixed tubular condenser C.

The length of the radiated wave could be varied by sliding this condenser along the rods, thereby changing the effective inductance in the circuit. The grid was connected to the filament by a variable resistance and a small choke D. The plate potential of 400–500 volts was transformed from the mains, rectified, and applied through the choke E to the junction of the inductance rod A and the plate lead. It was found that the filament chokes needed to be critically adjusted for each wavelength. Each filament lead was therefore constructed from a brass tube along the axis of which was a copper rod connected to the tube at one end and insulated from it at the other end. Along this rod and in contact with the inside of the tube, a small brass cylinder could

slide. The low-tension supply was connected to the rod, and the filament lead to the outside of the brass tube. The general arrangement of these filament chokes is shown in Fig. 3. The radiating aerial was coupled to the oscillating circuit by placing it a centimetre or so from the tubular condenser C and parallel to it. The oscillator was calibrated by coupling it to Lecher wires along which could slide a circular reflecting copper screen. This altered the effective length of the wires and gave very sharp current peaks in a vacuum thermojunction which was inserted in a wire bridge also capable of sliding along the Lecher wires.

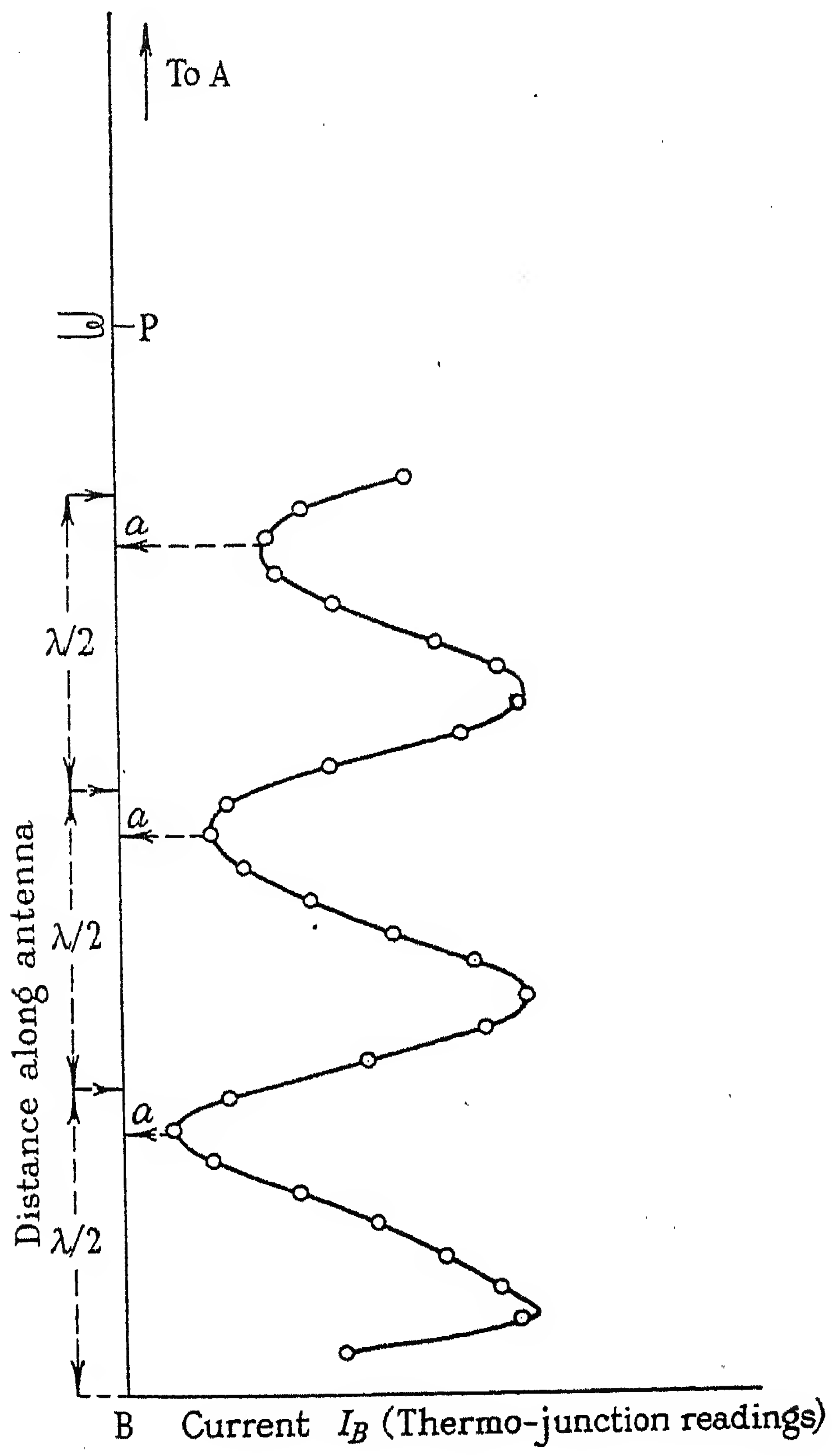

Fig. 4

$\lambda = 74$ cm.
$PB = 130$ cm.

(B) The Receiving Antenna

The brass-rod antenna was made in sections of varying lengths which screwed together in such a way that a vacuum thermojunction could be incorporated in the antenna at any required point, and could be moved along the antenna by unscrewing a portion from one end and screwing it on the other. The rod was 8 mm. in diameter. As an alternative method, the vacuum thermojunction was placed in a small bridge the ends of which slid along the antenna and made contact with it. The distance between the ends was about 2 cm.

(C) Experimental Procedure

With the transmitting antenna, experiments were made to test the three conclusions deduced from equations (3) and (4), namely:

(i) The sinusoidal nature of the current distribution, assuming $I = f(x)$.

(ii) The condition for maximum and minimum values of the currents I_A and I_B, assuming $I_A = f(PB)$ and $I_B = f(PA)$ respectively (see Fig. 1).

(iii) The dependence of the current on the total length of the antenna, assuming $I = f(l)$.

Finally, with the receiving antenna, the current distributions were measured for 7 values of l'/λ, varying from $0 \cdot 86$ to $2 \cdot 51$.

The results of the experiments with the transmitting antenna are shown in Figs. 4 to 8, and are discussed with reference to equations (3) and (4). The circles in Fig. 9 represent the experimental values of the current in a receiving antenna. Their distribution may be compared with the graphical representations of equations (5) and (7)—the dotted and full-line graphs respectively.

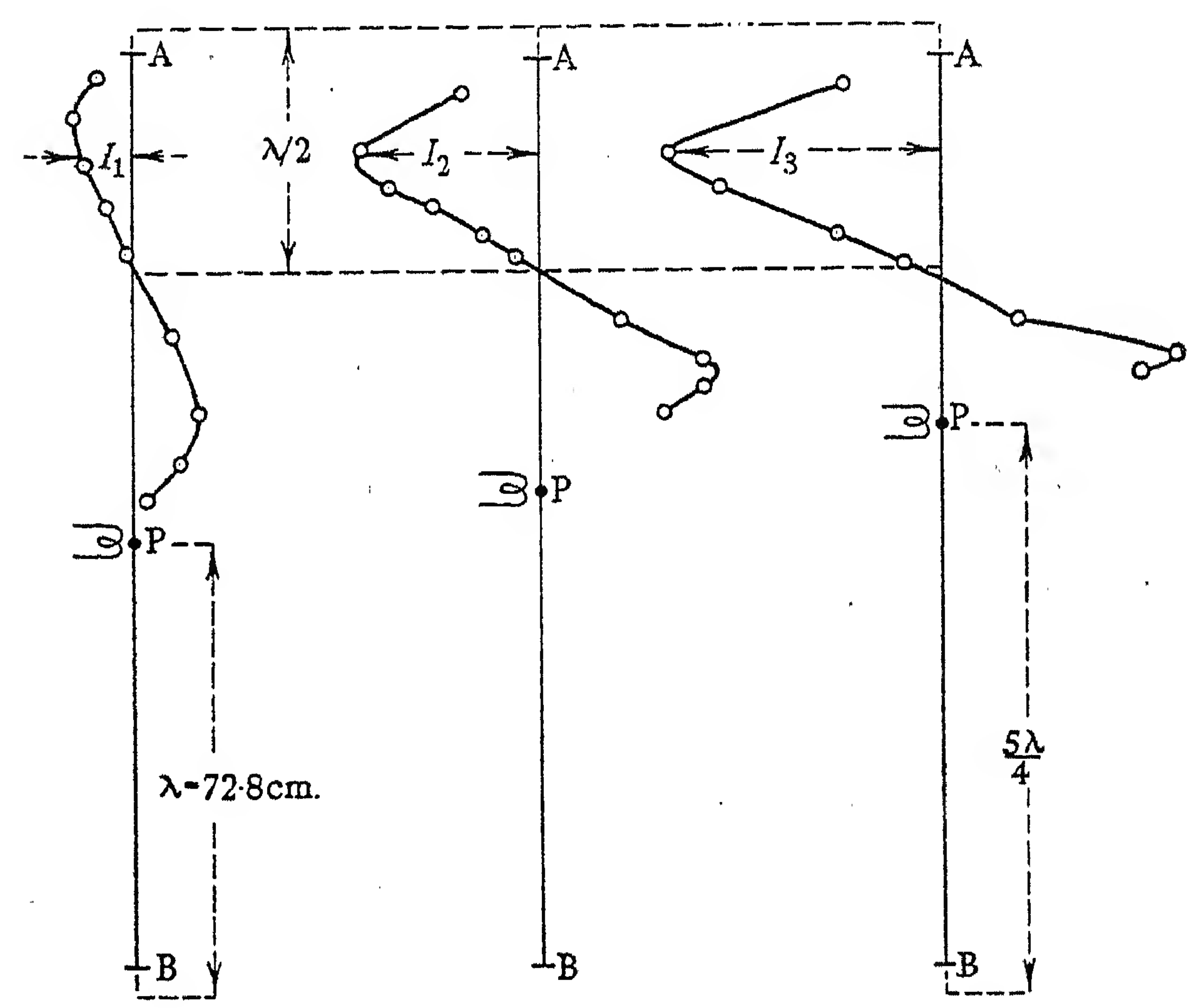

Fig. 5

(4) RESULTS

(A) Transmitting Aerial

(*a*). Fig. 4 shows the sinusoidal form of the current along one part of a transmitting antenna, and, except for the slight displacement a of the current curve, it confirms the accepted theoretical distribution for a distance of nearly 2 wavelengths. The displacement a is discussed when referring to Figs. 6 and 7 below. This graph was obtained by gradually moving a vacuum thermojunction along the antenna from B towards P, keeping the lengths AP and PB constant. The spacing of the current nodes at intervals of $\frac{1}{2}$ wavelength measured from the free end has already been shown by Wilmotte* for the first node in the case of an earthed transmitting antenna.

(*b*). Fig. 5 shows the same current distribution and

* See Reference (6).

also the fact that, in the portion PA of the antenna, the current I_A increases from a minimum I_1 to a maximum I_3 as the length of the other part PB increases from $n\lambda/2$ to $(2n + 1)\lambda/4$, n being 2 in this particular case. That the minimum value of I_1 is dependent on the length of the portion PB and is practically independent of the length PA in which the current I_1 is flowing, was shown by the fact that its variations (when PB is constant and equal to λ) were almost negligible as AP was increased in length from about 35 cm. to 110 cm. This is not because the portion AP has maximum impedance whatever be its length, but rather because the other portion PB has a constant minimum impedance, and the two portions may be considered to act as parallel loads. These variations of the current I_A in AP are more clearly shown in Fig. 6, where the length PB (or D) was gradually increased from about 8 cm. or less than $\frac{1}{8}$ wavelength to over 2 wavelengths. Currents I_1, I_2, and I_3, in this figure correspond to the values I_1, I_2, and I_3, respectively, in Fig. 5. The

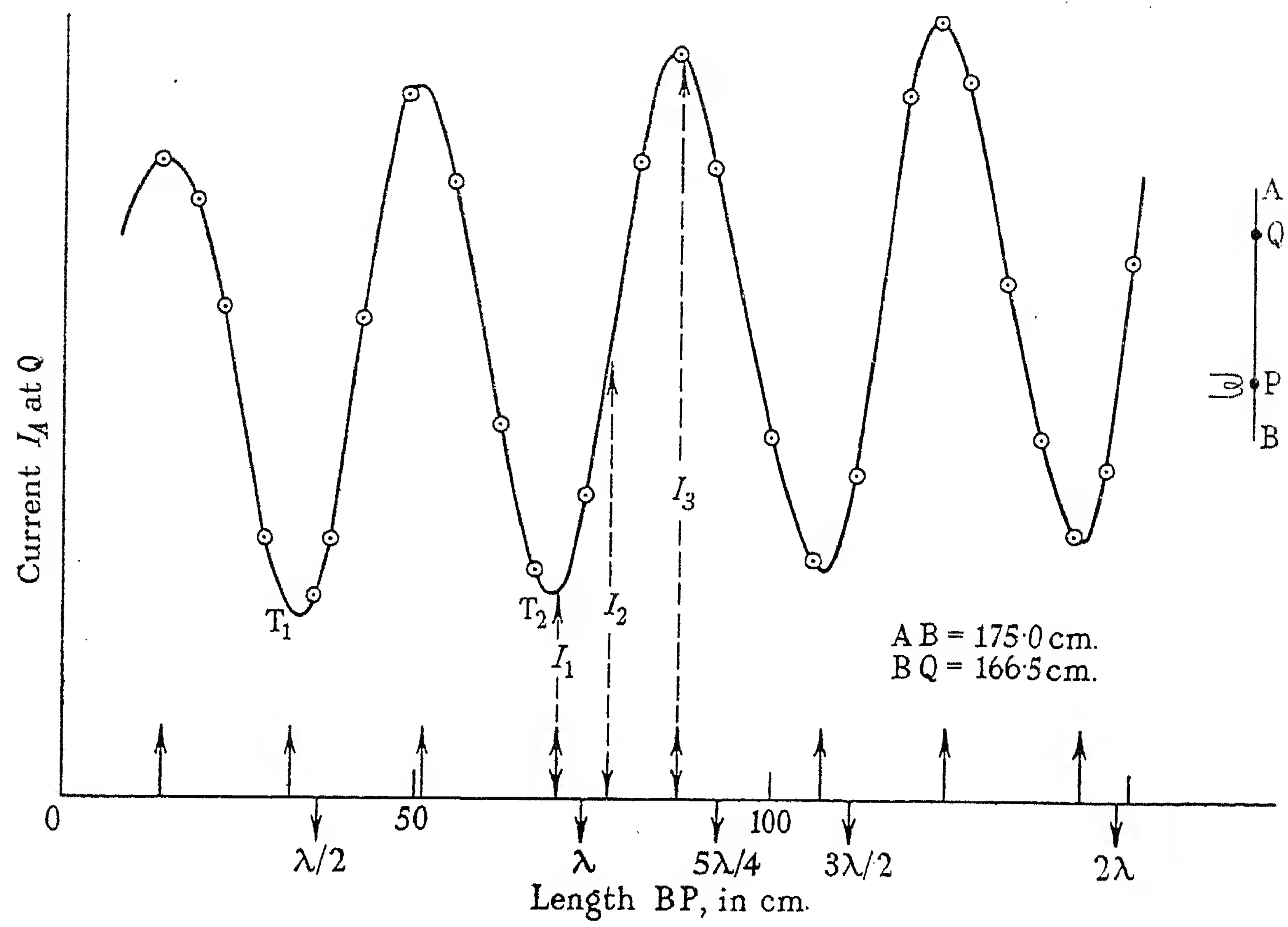

Fig. 6

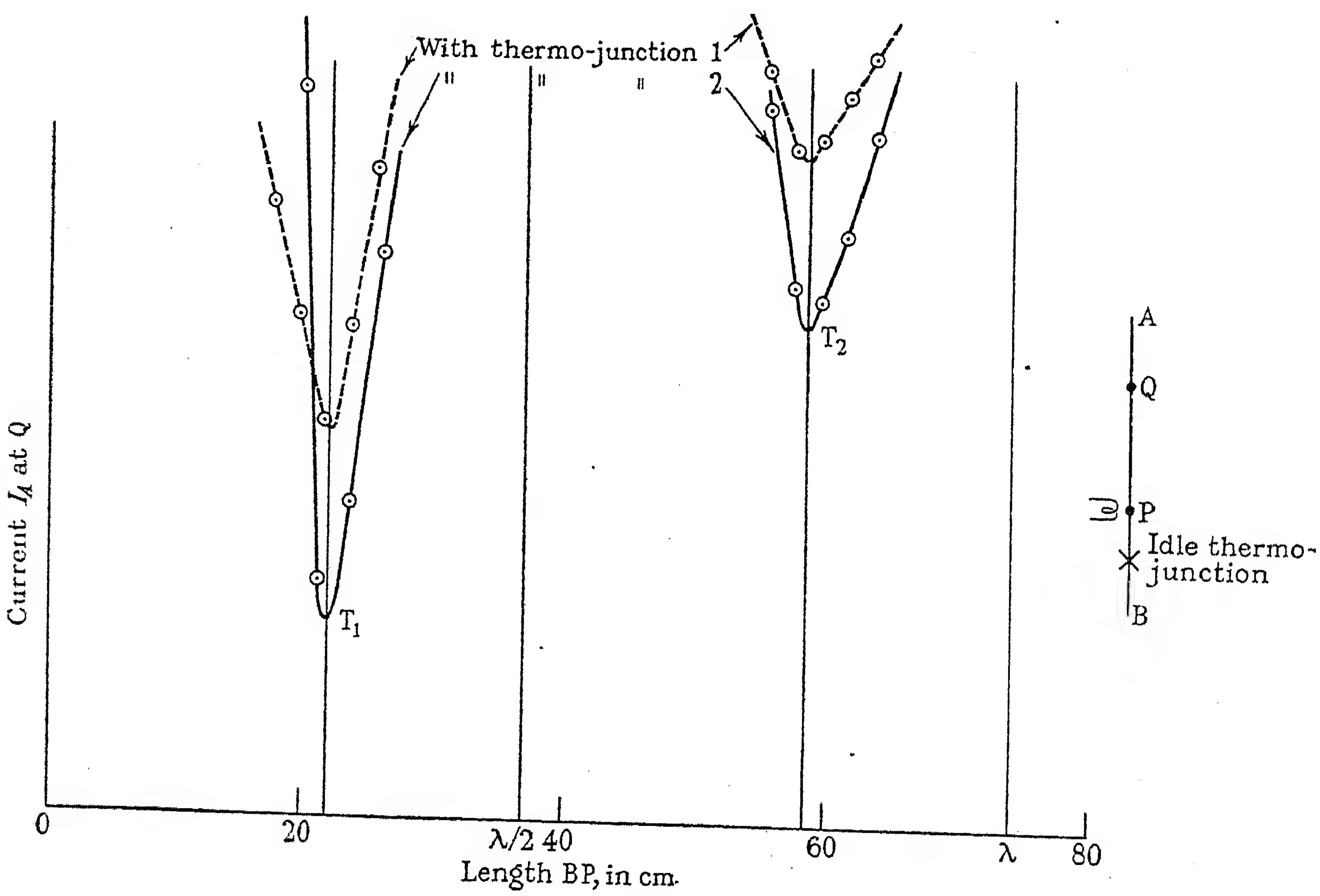

Fig. 7

AB = 175 cm.
BQ = 166·5 cm.

current I_A varies periodically with distance, the period being $\frac{1}{2}$ wavelength, but the turning points are displaced by 4 cm. from the positions calculated from the wavelength as measured on Lecher wires. The fact that the "equivalent" length of an antenna is greater than the geometrical length has been ascribed to various causes. Tani* states that "the wavelength of the wave on the antenna wire is markedly shortened as antenna insulators of large capacitance are used." Metzler† uses a reduced wavelength scale dependent on the velocity of wave propagation along the wires, whilst Hara‡ ascribes the effect to reflection from the earth and to the thickness of the aerial wire. All these factors produce a kind of shortening effect which is operative throughout the length of the antenna and may be measured in equivalent centimetres of antenna wire. But with the present experiments such effects are negligible compared with that produced at the ends of the antenna, and by far the largest change in the equivalent length was produced by altering the shape of the end of the wire. We believe that over 90 % of the effect referred to here is due to the fact that, on reflection of the waves from the end of the antenna, the phase-change is not exactly π and the resultant current at the end is not zero. Tani referred to a similar end-effect and stated that he obtained a shortening factor of 3·8 % when "a capacitance of 2·87 $\mu\mu$F was placed at the end of the antenna." It would seem desirable to distinguish the distributed "shortening effect" from the localized "end effect." It is significant that, when both ends of the antenna are involved, the effect is almost exactly doubled. The value of 4 cm. is therefore the value of a in equation (6) and the equivalent phase-change on reflection with this antenna was therefore 1·11 π, the wavelength being 72·8 cm. Apart from this "end effect," which is now being investigated further, Figs. 4, 5, and 6, give support to the conclusions (*a*) and (*b*) deduced on page 416 from equations (3) and (4).

Fig. 7 is similar to a part of Fig. 6, and shows the new positions of troughs T_1 and T_2 in the latter figure when an idle thermojunction (with leads and ammeter) was inserted in the portion PB of the antenna. The difference in the positions of these troughs in Figs. 6 and 7 gives the equivalent length of the idle thermojunction in centimetres of antenna wire. From the figure this is seen to be about 11 cm. for each junction. Hence b in equation (7) is equal to 5·5 cm.

Thus a total correction of 19 cm. is necessary when both corrections arise, as, for example, in the current distribution measurements in a long receiving antenna where there are two end-effects and one thermojunction correction.

(*c*). The third deduction which was made from equations (3) and (4) was based on the fact that $I_A \propto \operatorname{cosec} 2\pi l/\lambda$ when D and $(l - x)$ in equation (3) were kept constant. This was tested experimentally by gradually increasing the length of the portion PQ of the antenna (Fig. 1), thereby keeping AQ [or $(l - x)$] and BP (or D) constant. The current should reach infinity for values of $l/\lambda = n\lambda/2$ and should have some constant minimum values for $l/\lambda = (2n + 1)\lambda/4$. Resistances will of course modify these theoretical conclusions concerning infinite current values, and the experimental results (corrected for the end-effects and thermojunction) are shown in Fig. 8.

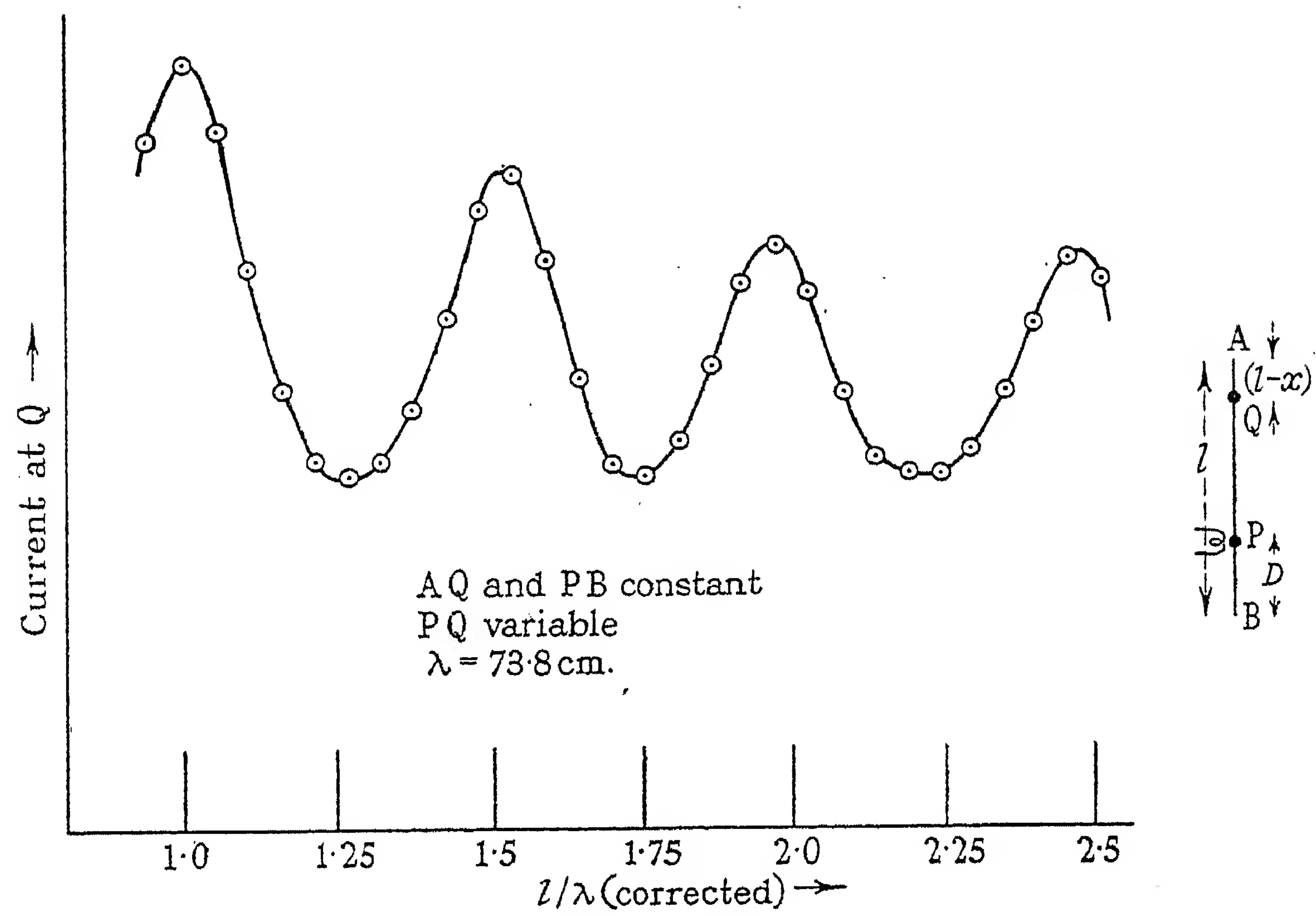

Fig. 8

(B) Receiving Aerial

For testing equations (5) and (7) a vacuum thermojunction was gradually moved along the rod antenna which was used as a receiving aerial at a distance of several wavelengths from the transmitter. To move the thermojunction a portion of the rod was unscrewed from one end and screwed in the other, and the aerial adjusted so that its position remained fixed with respect to the transmitter.

In Fig. 9 the experimental values so obtained are

* See Reference (8). † *Ibid.*, (2). ‡ *Ibid.*, (3).

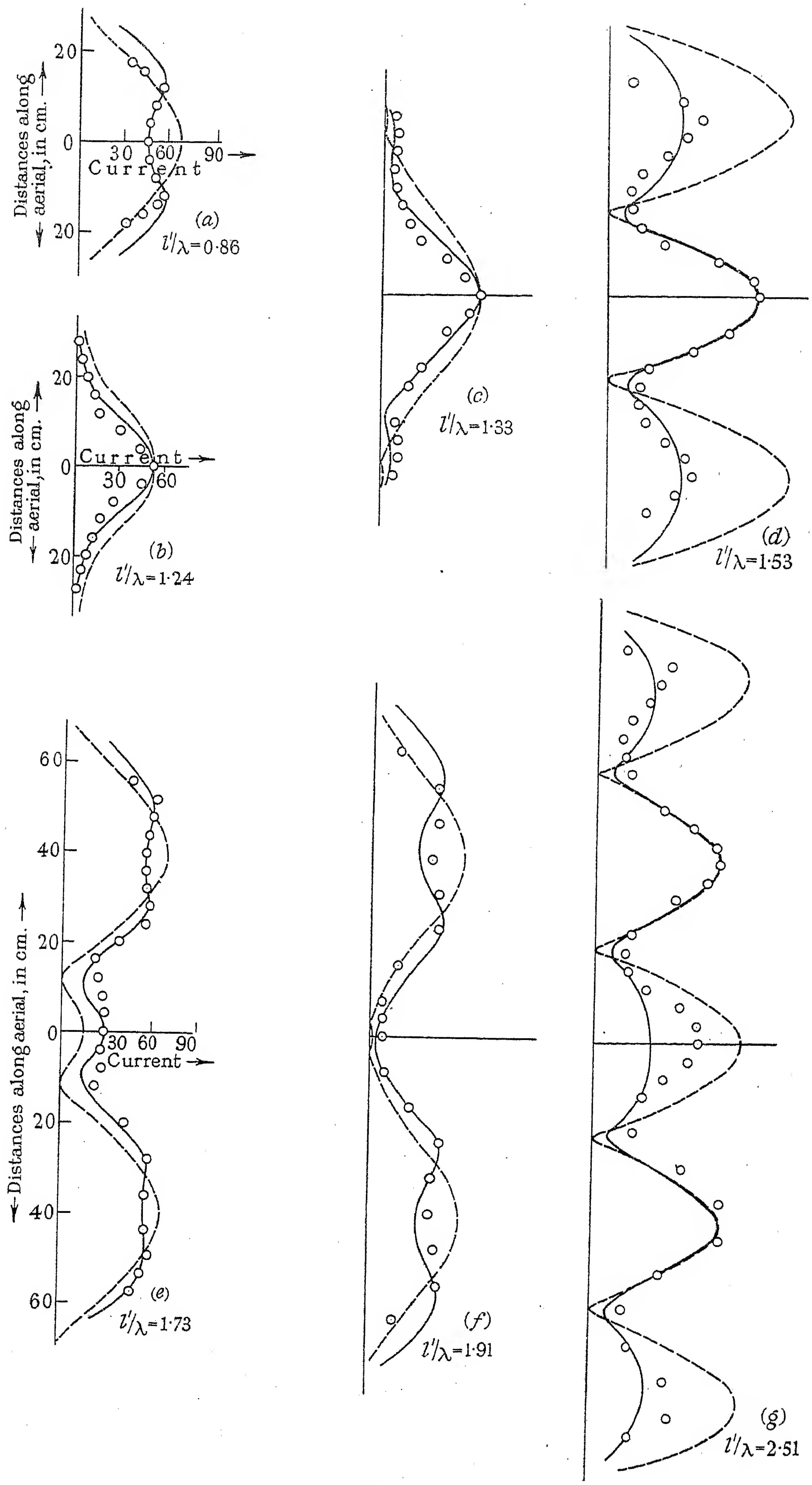

Fig. 9

- - - equation (5).
—— equation (7).
ooo experimental measurements.

shown by the small circles, whilst the graphs are plotted from equations (5) and (7). It is seen that the results of the experiments agree reasonably well with the latter equation.

(5) CONCLUSIONS

In general, the experimental results discussed in Section (4) seem to lend support to the theories put forward in Section (2). Consequently, it may be assumed (i) that the currents in a transmitting antenna are practically zero at the free ends, with nodes and antinodes spaced alternately along the antenna wire at $\frac{1}{4}$-wavelength intervals, (ii) that the current is sinusoidally distributed along the two portions of a transmitting antenna which are separated by the point of energy input, and (iii) that the currents in the two portions are dependent upon each other in the manner indicated by equations (3) and (4).

In the case of an isolated receiving antenna energized by a uniform radiation field, the current is distributed approximately as indicated by equation (5), or more accurately by equation (6), and current nodes occur at the free ends and at intervals of one whole wavelength measured from both ends of the antenna.

REFERENCES

(1) E. B. MOULLIN: "On the Current induced in a Wireless Telegraph Receiving Antenna," *Proceedings of the Cambridge Philosophical Society*, 1925, vol. 22, p. 567.

(2) E. METZLER: "Stationary and Progressive Waves in Antennae," *Bulletin Technique des Télégraphes et Téléphones Suisses*, 1936, vol. 14, p. 161.

(3) G. HARA: "Radiation and Line Constants of Linear Conductor Systems, and Applications to Antenna Problems," *Memoirs of the Ryojun College of Engineering*, 1936, vol. 9, p. 121.

(4) F. M. COLEBROOK: "An Experimental and Analytical Investigation of Earthed Receiving Aerials," *Journal I.E.E.*, 1932, vol. 71, p. 235.

(5) J. LABUS: "Calculation of the Impedance of Antenna Systems," *Zeitschrift für Hochfrequenztechnik und Elektroakustik*, 1933, vol. 41, p. 17.

(6) R. M. WILMOTTE: "The Distribution of Current in a Transmitting Antenna," *Journal I.E.E.*, 1928, vol. 66, p. 617.

(7) N. VON KORSHENEWSKY: "On the Vibrations of an Oscillator in a Radiation Field," *Zeitschrift für Technische Physik*, 1929, vol. 10, p. 604.

(8) K. TANI: "Theory of the Complex Antenna," *Report of Radio Research in Japan*, 1933, vol. 3, p. 19.

MULTIPLE REFLECTIONS BETWEEN TWO TUNED RECEIVING ANTENNAE*

By Professor L. S. PALMER, D.Sc., Ph.D., Member, W. ABSON, and R. H. BARKER.

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SUMMARY

A consideration of previous work on the reflecting action of an idle or parasitic receiving antenna suggested the desirability of investigating the extent to which multiple to-and-fro reflections between parallel receiving antennae affect the currents produced in them. In order to avoid the possible errors arising from the assumption that tuned half-wave antennae act as Hertzian dipoles, the values of the mutual impedances and phase differences deduced by Carter and tabulated by Tani are used in the present work.

By considering the effects of multiple reflections between two tuned receiving antennae, formulae for the antenna currents are obtained in terms of the currents produced in the antennae when isolated, the distance between the antennae, the wavelength, and the orientation of the plane containing the antennae to the direction of wave propagation.

The validity of these formulae was tested by experiments with electromagnetic waves 80 cm. in length, The experimental results are compared with the graphical representations of the formulae, and for antenna spacings greater than about one-quarter of the wavelength, it is concluded that (i) the effects of multiple reflections do not appreciably affect the optimum or critical spacings between the antennae, but must be taken into account when determining the antenna currents, and (ii) tuned antennae may be considered to act as Hertzian dipoles.

With parallel tuned antennae oriented with the line joining them parallel to the direction of wave propagation, the optimum distances between them for maximum current in the leading antenna are $0 \cdot 31\lambda$, $0 \cdot 85\lambda$, $1 \cdot 36\lambda$, $1 \cdot 87\lambda$, etc. In the trailing antenna the current gradually increases as the antenna. spacing increases above a value somewhat less than $0 \cdot 2\lambda$ For maximum current in either antenna when oriented with the line joining them perpendicular to the direction of wave propagation, the optimum spacings are $0 \cdot 67\lambda$, $1 \cdot 71\lambda$, etc., and for other orientations the current variations with antenna spacing are determined by equations (4) and (6) when the field is uniform, and by equations (5) and (7) when the field is not uniform.

(1) INTRODUCTION

The advent of short-wave beam antenna systems has led to the publication of many papers on the radiation impedance and directional properties of various kinds of antenna arrays consisting of two or more parallel wires. Since the early work of Abraham† and others, perhaps the most important contributions to the subject are those of Bontsch Bruewitsch,‡ Wilmotte and McPetrie,§ Pistolkors,|| Beckmann,¶ Carter,** Tani,†† Brown and King,† and Brown‡ all of whom deal essentially with questions of radiation impedance and its dependence on antenna spacings, current distributions and phase differences. In practice, it is usual with transmitting antennae to determine the antenna spacing appropriate to a specified phase difference and to space and feed the antennae accordingly. With a tuned idle or parasitic reflecting antenna (whether used in a transmitting or receiving array) the phase difference is automatically determined by the ratio of the distance between the antennae to the length of the wave. This was discussed by Englund and Crawford§ in America and by Palmer and Honeyball|| independently in August 1929. The object of the latter authors was to determine the optimum spacing between two parallel tuned receiving antennae. The theoretical treatment was approximate because, firstly, the antennae were assumed to act as Hertzian dipoles, and, secondly, when the current in either antenna is represented mathematically by an infinite series of terms which may be assumed to represent the effects of an infinite number of to and fro reflections between the antennae, then the previous treatment only considered the first term of the series. In other words, the initial effect of one antenna upon the other was alone considered and not the effect of multiple reflections between them. These multiple reflections, although of progressively decreasing importance, do affect the value of the currents produced in the antennae.

Carter¶ considered the finite length of each antenna and deduced expressions for the radiation impedance and for the phase difference between the antenna currents. Tani** and Brown and King†† developed similar theories, and the former tabulated the values of the mutual resistance and reactance for various antenna spacings and lengths. Because it seems that Carter's assumptions approximate more closely to the actual experimental conditions than the assumptions underlying the dipole theory, Carter's formulae (using Tani's tables) have been adopted in the present work.

None of the authors cited above has treated the problem of two antennae from the point of view of multiple to-and-fro reflections. In the most recent work‡‡ Brown states "The current in antenna 1 is so weak that the reaction back into the antenna 0 is negligible." This is not necessarily true, because the current in antenna 1 may be nearly as great as that in antenna 0. Consequently it was felt desirable to extend the previous work of Palmer and Honeyball by considering multiple reflections and by adopting the more exact expressions for the

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† See Reference (1). ‡ *Ibid.*, (2). § *Ibid.*, (3). || *Ibid.*, (4). ¶ *Ibid.*, (5). ** *Ibid.*, (6). †† *Ibid.*, (7).

† See Reference (8). ‡ *Ibid.*, (9). § *Ibid.*, (10). || *Ibid.*, (11). ¶ *Ibid.*, (6). ** *Ibid.*, (7). †† *Ibid.*, (8). ‡‡ *Ibid.*, (9).

mutual impedance and radiation field which have since been developed by Carter, Tani, and Brown and King. It should then be possible, in the mathematical expression for the antenna current, to determine the importance of those terms representing subsidiary reflections by comparing the experimental values of the optimum antenna spacings with the results previously obtained.

The method of analysis employed may be regarded as an analytical expedient. It is not suggested that by multiple reflections the currents in the antennae take a finite time to attain their measured values.

(2) THEORETICAL CONSIDERATION

In order to determine the antenna current produced by any given radiation fields, it is obviously necessary to have a knowledge of the antenna impedance and of the factors upon which it depends. This question has already been the subject of much previous work (see above). In order to simplify the experimental work, a direct determination of the antenna impedance was rendered unnecessary by comparing the current produced in two antenna when both are present with the current produced in either antenna when isolated. This procedure was employed by Brown* and involves the usual assumption, namely that, in the neighbourhood of one receiving antenna, the component of the field due to the distant transmitter is not appreciably affected by the proximity of the other receiving antenna. The experimental results of most authorities seem to justify this assumption, at least for distances between the antennae which exceed about $0 \cdot 2\lambda$.

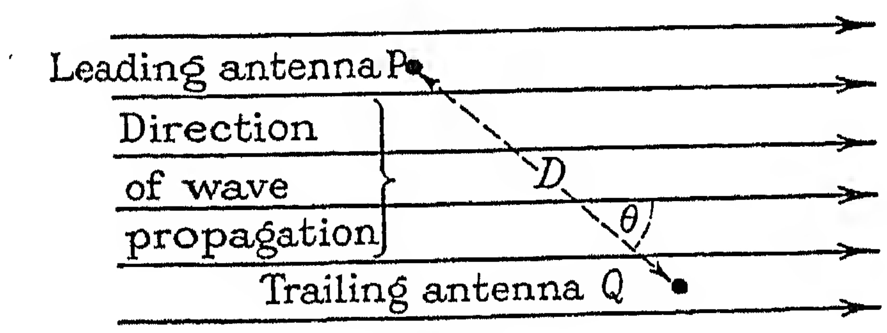

Fig. 1

In what follows the "dashed" symbols (e.g. I') refer to the antennae when isolated and the "undashed" symbols to the antennae when both are present.

In Fig. 1, P and Q are two identical tuned half-wave linear antennae situated in a uniform electromagnetic field polarized with its electric vector parallel to the antennae. This field is produced by some distant transmitter T.

Suppose the antennae are a distance D apart and the plane containing them is oriented at an angle θ to the direction of wave propagation.

Then, with antenna Q (say) absent, let the current produced in the antenna P be ${}_PI' = {}_PI'_0 \sin \omega t$. At a distance D from P the field due to the re-radiation from P will be proportional to $A_PI'_0 \sin(\omega t - \beta)$, where, for a given antenna, A and β are functions of the distance D and the wavelength λ. According to the dipole theory of Hertz, these constants are given by†‡

$$A = \left(\frac{1}{a^2} - \frac{1}{a^4} + \frac{1}{a^6}\right)^{\frac{1}{2}} \text{ and } \beta = \left(a - \arctan \frac{a^2 - 1}{a}\right)$$

where $a = 2\pi D/\lambda$. Pistolkor's* expressions for A and β reduce to $A = (a^2 + \pi^2/4)^{-\frac{1}{2}}$ and $\beta = (a^2 + \pi^2/4)^{+\frac{1}{2}}$ whilst Tani† gives tables of values of A and β for different ratios of D/λ in terms of R_{PQ} and X_{PQ}—the radiation resistance and reactance respectively of the aerial array PQ. In Carter's‡ and Tani's§ papers

$$A = (R_{PQ}^2 + X_{PQ}^2)^{\frac{1}{2}} \text{ and } \beta = \arctan(-X_{PQ}/R_{PQ})$$

If now the antenna Q be placed near P, it will be influenced both by the field from the distant transmitter T and by the re-radiated field from P. That is, the current in Q from these two component fields will be given by the vector sum

$${}_QI'_0 \sin(\omega t - \alpha) + AB_PI'_0 \sin(\omega t - \beta)$$

where ${}_QI'_0$ is the amplitude of the current produced in the antenna Q by the field from the transmitter T, and α is the phase difference $2\pi D \cos\theta/\lambda$. In the second term, B is a constant involving the resistance of the antenna Q, and the wavelength, but is independent of the distance D. In addition to these two component fields in the neighbourhood of Q, there will be other component fields of less magnitude due to the re-radiation from P of energy it has received from Q. The initial current ${}_QI'_0 \sin(\omega t - \alpha)$ in Q will produce a current $AB_QI'_0 \sin(\omega t - \alpha - \beta)$ in P, which, in turn, will re-radiate to Q, producing a current

$$A^2B^2{}_QI'_0 \sin(\omega t - \alpha - 2\beta).$$

Thus the final current ${}_QI$ in Q may be considered to be the resultant of an infinite series of component currents, i.e.

$$\begin{aligned} {}_QI = {}_QI'_0 \sin(\omega t - \alpha) + AB_PI'_0 \sin(\omega t - \beta) \\ + (AB)^2{}_QI'_0 \sin(\omega t - \alpha - 2\beta) + (AB)^3{}_PI'_0 \sin(\omega t - 3\beta) \\ + (AB)^4{}_QI'_0 \sin(\omega t - \alpha - 4\beta) + \ldots \quad . \quad . \quad . \quad (1a) \end{aligned}$$

Similarly

$$\begin{aligned} {}_PI = {}_PI'_0 \sin \omega t + AB_QI'_0 \sin(\omega t - \alpha - \beta) \\ + (AB)^2{}_PI'_0 \sin(\omega t - 2\beta) + (AB)^3{}_QI'_0 \sin(\omega t - \alpha - 3\beta) \\ + (AB)^4{}_PI'_0 \sin(\omega t - 4\beta) + \ldots \quad . \quad . \quad . \quad (1b) \end{aligned}$$

These series may be summed quite readily in the special case when $\theta = 90°$, that is, when the plane containing the antennae is perpendicular to the direction of wave propagation, but the exact summations for any other values of θ (or α) are somewhat cumbersome.

When $\theta = 90°$, we have the simplifications:—

$$\alpha = 0, \ {}_PI'_0 = {}_QI'_0 = I'_0, \text{ and } {}_PI_0 = {}_QI_0 = I_0$$

Hence the amplitude I_0 of the current in either antenna in the presence of the other is given by

$$I_0 = I'_0[1 - 2AB\cos\beta + (AB)^2]^{-\frac{1}{2}} \quad . \quad . \quad (2)$$

In this equation I_0 and I'_0 can be directly measured, whilst A and β are known constants. B can thus be determined.

In a non-uniform radiation field the second two simplifications may not be justified even when $\theta = 90°$. In this case, let ${}_QI'_0/{}_PI'_0 = C$, where C is not now equal to

* See Reference (9).
† See p. 1046 of Reference (11).
‡ See p. 387 of Reference (12).

* See p. 566 of Reference (4).
† See pp. 23 and 73 *et seq.* of Reference (7).
‡ See pp. 1010 and 1016 of Reference (6).
§ See Reference (7).

unity. Then equation (2) must be replaced by the equations

$$_PI_0 = {_PI_0'}[1 - 2ABC\cos\beta + (ABC)^2]^{-\frac{1}{2}} \quad . \quad (3a)$$

and $$_QI_0 = {_QI_0'}\left[1 - 2\frac{AB}{C}\cos\beta + \left(\frac{AB}{C}\right)^2\right]^{-\frac{1}{2}} \quad . \quad (3b)$$

Thus, if $_PI_0$ and $_PI_0'$ be measured directly and the value of $({_PI_0^2} - {_PI_0'^2})/{_PI_0^2}$ be calculated, the validity of equation (3*a*) may be tested by the linearity of the graph obtained by plotting the above function of the currents against the expression $[2AC\cos\beta - B(AC)^2]$, treating the latter expression as a function of C and D/λ. The value of the constant B can be determined from equation (2) or from equations (6) and (7) (see below). In a similar way equation (3*b*) may also be tested.

For values of θ other than 90°, the right-hand sides of equations (1) may be summed approximately by making the assumption that terms involving $(AB)^3$ and higher powers can be neglected. This is equivalent to neglecting all reflections after the first two, a procedure which is justified because experiments have shown that $(AB)^3 < 0\cdot01$. Consequently, if the antennae are situated a distance from the transmitter which is very great compared with the distance between them and the radiation field is assumed to be constant over the distance PQ (Fig. 1), then $_PI_0' = {_QI_0'} = I_0'$ and

$$_PI_0 \simeq I_0'[1+2AB\cos(\alpha+\beta)+(AB)^2(1+2\cos 2\beta)]^{\frac{1}{2}} \quad (4a)$$

and

$$_QI_0 \simeq I_0'[1+2AB\cos(\alpha-\beta)+(AB)^2(1+2\cos 2\beta)]^{\frac{1}{2}} \quad (4b)$$

If the radiation field in which the antennae are situated is not uniform then $_PI_0' \neq {_QI_0'}$ and equations (4) must be replaced by

$$_PI_0 = {_PI_0'}[1+2ABC\cos(\alpha+\beta)+(AB)^2(C^2+2\cos 2\beta)]^{\frac{1}{2}} \quad . \quad . \quad (5a)$$

and

$$_QI_0 = {_QI_0'}\left[1+2\frac{AB}{C}\cos(\alpha-\beta)+(AB)^2(C^{-2}+2\cos 2\beta)\right]^{\frac{1}{2}} \quad . \quad . \quad (5b)$$

where $C = {_QI_0'}/{_PI_0'}$ as before. These equations reduce to equations (3) when $\alpha = 0$.

In order to test experimentally the validity of equations (4), it is useful to combine them together, with the consequent elimination of the terms involving $(AB)^2$. We then get

$$\frac{{_QI_0^2} - {_PI_0^2}}{I_0'^2} = 4AB\sin\alpha\sin\beta \quad . \quad . \quad (6)$$

Similarly equations (5) become

$$\frac{({_QI_0^2} - {_PI_0^2}) - ({_QI_0'^2} - {_PI_0'^2})}{{_PI_0'}\,{_QI_0'}} = 4AB\sin\alpha\sin\beta \quad . \quad (7)$$

In equations (6) and (7) all the currents can be measured and the appropriate function can be plotted against $\sin\alpha[= f(\theta)]$, keeping D/λ and therefore A and $\sin\beta$ constant. Thus the dependence of the currents upon the orientation θ of the plane containing the antennae to the direction of wave propagation may be tested by the linearity of the resulting graph, and the constant B can be determined from its slope.

(3) EXPERIMENTAL WORK

(a) Apparatus

In order to test the foregoing conclusions concerning the values of the currents in two parallel tuned antennae, it was decided to work on ultra-short waves in order to reduce the size of the necessary apparatus to manageable dimensions. For this reason a valve oscillator was used which operated on a wavelength range of from 60 to 100 cm.* The radiating circuit consisted of a half-wave antenna placed at the focus of a cylindrical parabolic reflector of $2\frac{1}{2}\lambda$ aperture and $\frac{3}{4}\lambda$ focal length. The antenna was fed by feeder lines one wavelength long which protruded $\frac{1}{4}\lambda$ through the back of the reflector and the whole apparatus was elevated about $2\frac{1}{2}$ m. (or about 3λ) above the ground, in order to minimize ground reflection effects. From previous experiments† in the locality, reflections from the ground were found to be negligible at heights greater than about $2\frac{1}{2}\lambda$.

The receiving antennae consisted of short brass rods which were mounted vertically on a wooden arm capable of rotating in a horizontal plane about a vertical axle through its centre. The revolving arm was at such a height above the ground that the antennae were level with the transmitter. The two antennae could slide along the arm, thereby changing the distance D between them, whilst the rotation of the arm controlled the value of θ. The currents were measured by inserting vacuum thermojunctions at the centre of the antennae, and arrangements were made for the d.c. leads to remain perpendicular to the antennae as they rotated. In order to get a tuned half-wave antenna, the length of the rod was gradually adjusted until the current recorded was a maximum. The geometrical length was then found to be about 19 cm. shorter than $\lambda/2$. This difference in length agreed with the similar value determined by Palmer and Gillard‡ using the same wavelengths with similar apparatus.

(b) Experimental Results

When an isolated antenna was moved about in the locality in which the experiments with two antennae were to be carried out, it was found that the current in the isolated antenna did not remain constant. No adjustment of the reflector or transmitting aerial would make the field sufficiently uniform. Owing to this inability to obtain a sufficiently uniform field throughout the region in which the receiving antennae were situated, it was not possible to check directly the validity of equations (2), (4), and (6). These equations assume $_PI_0' = {_QI_0'}$ (or $C = 1$). Consequently values of $_PI_0'$ and $_QI_0'$ were recorded independently and experiments were undertaken to test the validity of equations (3), (5), and (7), which do not assume that $_PI_0' = {_QI_0'}$.

(i) Antenna oriented so that $\theta = 90°$.

The receiving antennae were set up at a distance of about 6 or 8 m. from the transmitter, so that the plane

* The details of this oscillator are described by Palmer and Gillard in their paper on page 415.

† See page 70 of Reference (14). ‡ See page 421 of Reference (13).

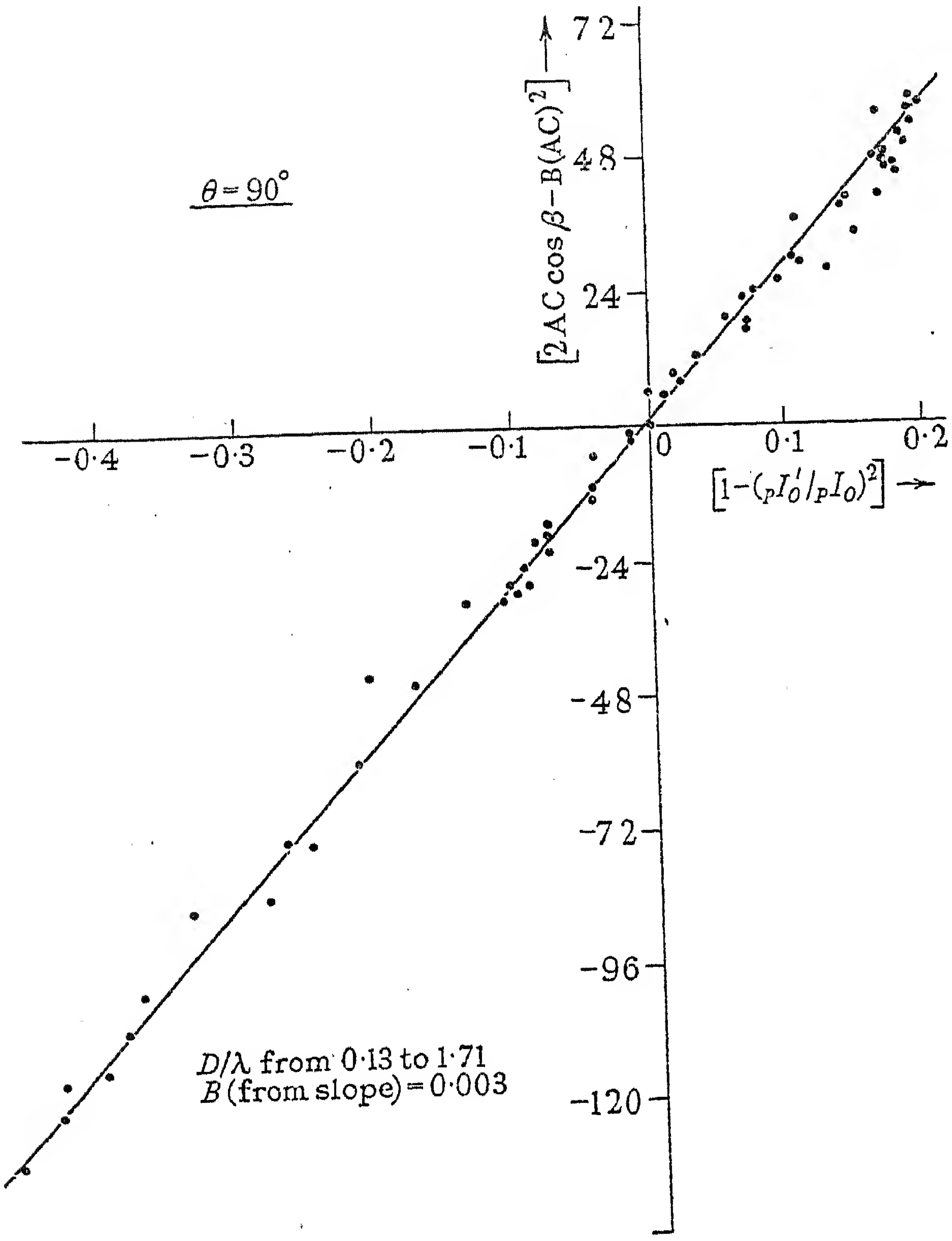

Fig. 2

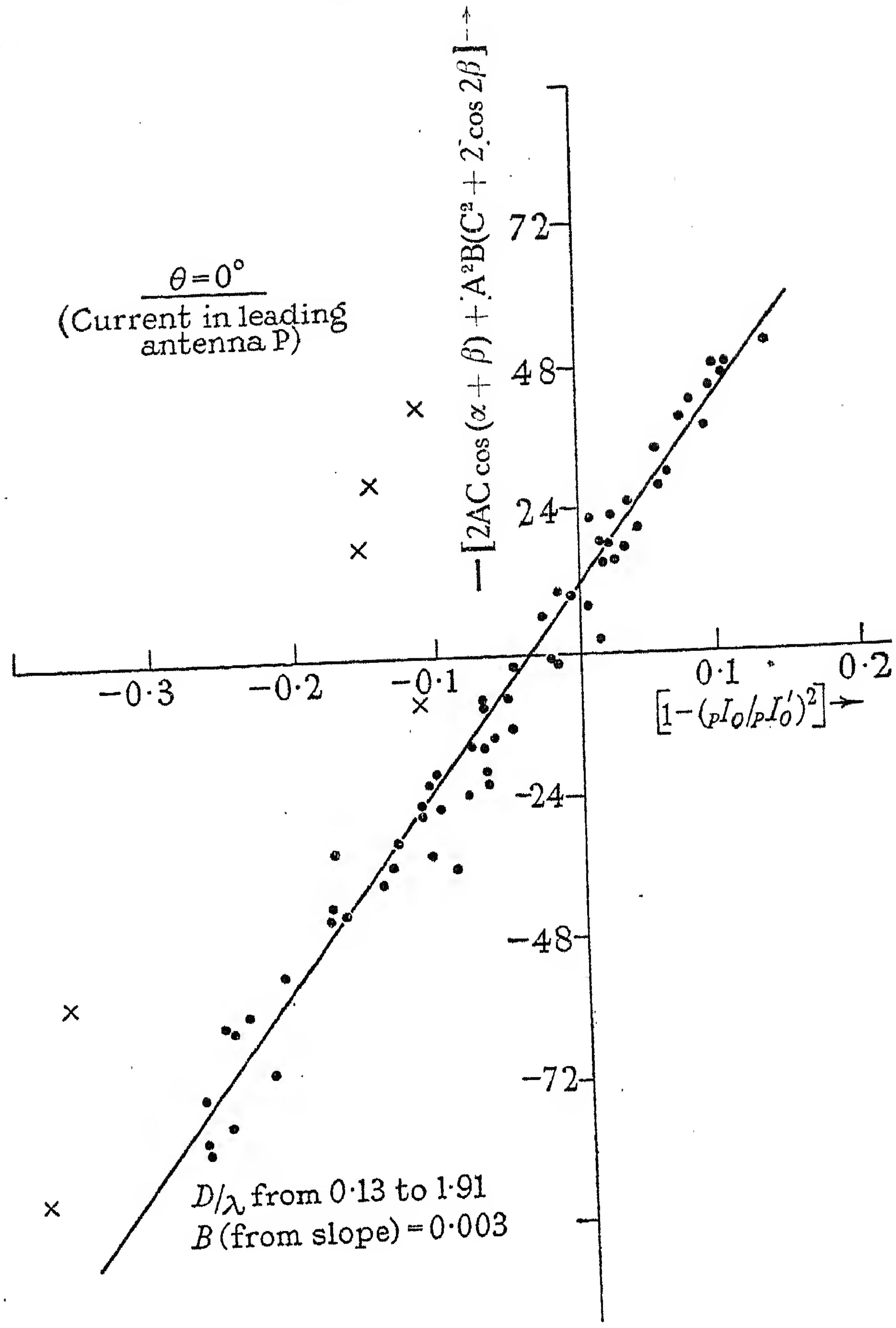

Fig. 4

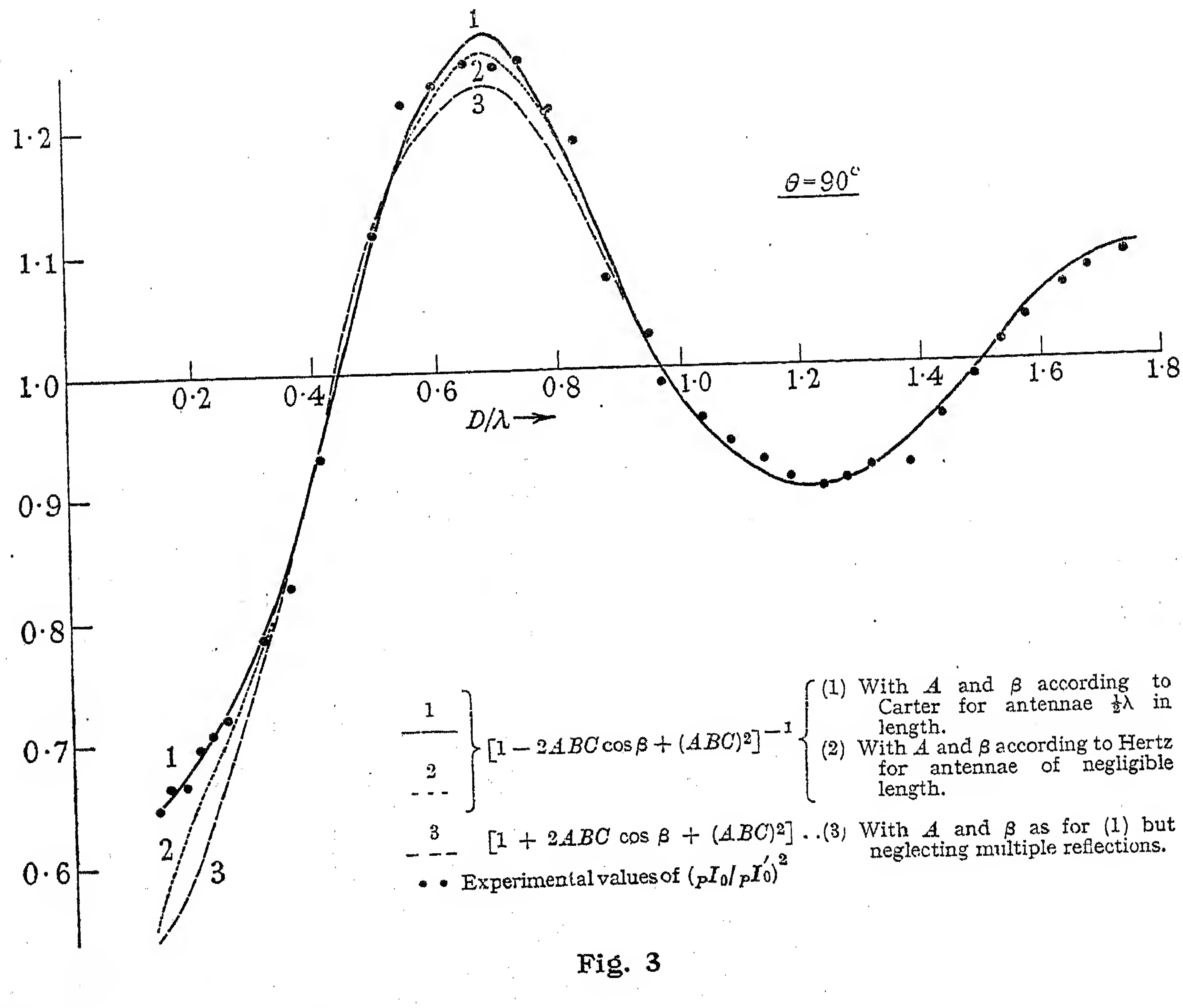

Fig. 3

containing the antennae was perpendicular to the direction of wave propagation ($\theta = 90°$). Measurements of ${}_PI_0$ (or ${}_QI_0$) were taken for 62 values of D/λ, ranging from $0{\cdot}13$ to $1{\cdot}71$, and after each observation one antenna was removed and the value of ${}_PI_0'$ (or ${}_QI_0'$) was then read. The function $[1-({}_PI_0'/{}_PI_0)^2]$ plotted against $[2AC\cos\beta - B(AC)^2]$ is shown in Fig. 2, which is a linear graph to within the errors of experiment. In this graph there is no indication of the values of D/λ for which the current ${}_PI_0$ (or the ratio ${}_PI_0/{}_PI_0'$) is a maximum or a minimum. Consequently the same data have been replotted in Fig. 3 so as to show the variation of the current ${}_PI_0$ with increasing values of the ratio D/λ. The full-line graph is that

is in contrast with the lack of agreement for such small values of D/λ when the plane containing the antennae is not perpendicular to the direction of wave propagation and $\theta \neq 90°$ (see Figs. 5, 7, and 9).

(ii) Antennae oriented so that θ = 0°.

Similar experiments were carried out with the receiving antennae and transmitting aerial all in line. Sixty-seven measurements of ${}_PI_0/{}_PI_0'$ for values of D/λ ranging from $0{\cdot}13$ to $1{\cdot}91$, and 33 measurements of ${}_QI_0/{}_QI_0'$ for values of D/λ from $0{\cdot}13$ to $1{\cdot}27$, were taken. The data are plotted as linear graphs in Figs. 4 and 6 and with D/λ as abscissae in Figs. 5 and 7 respectively.* In

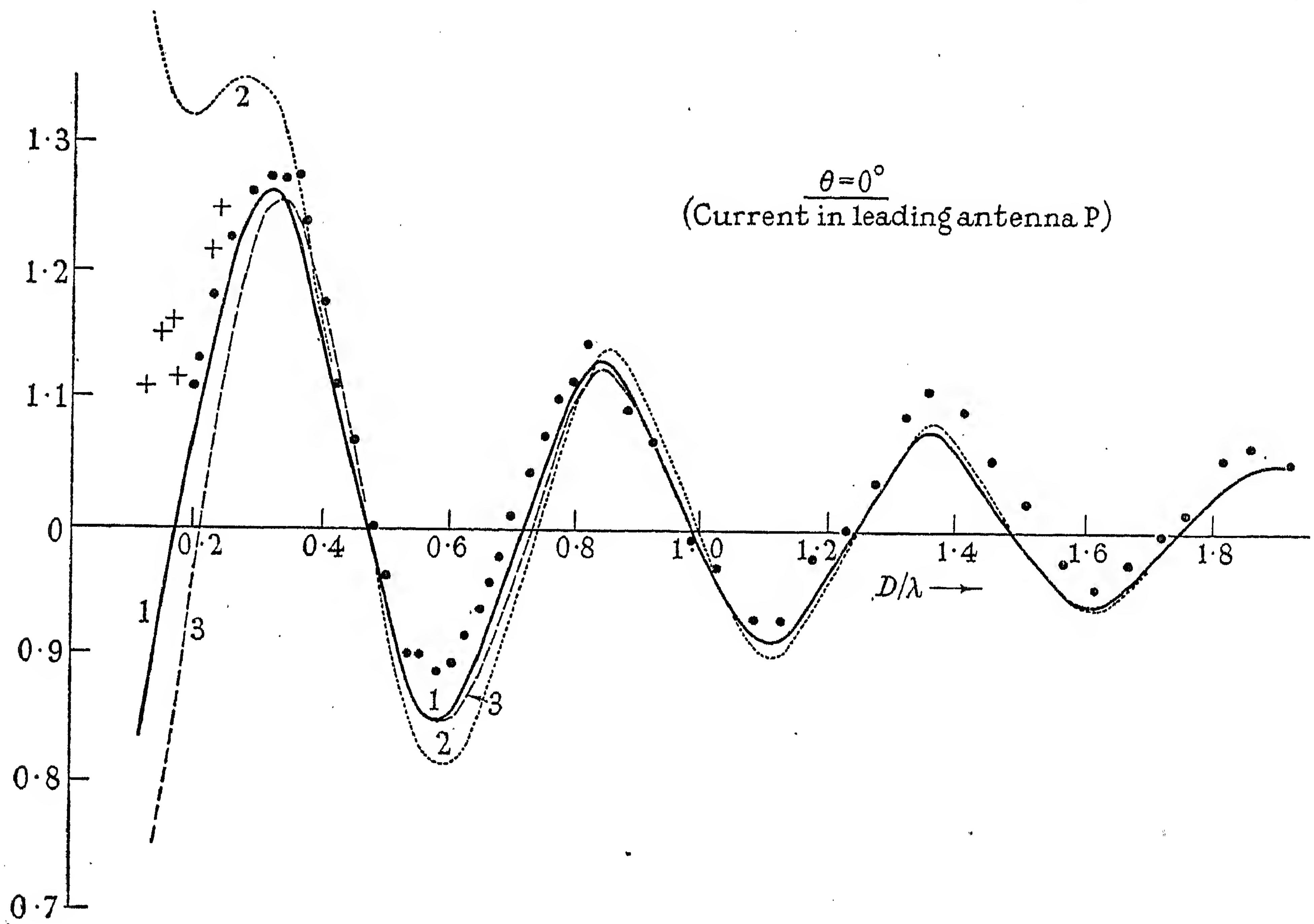

Fig. 5

1 —— $[1 + 2ABC\cos(\alpha+\beta) + (AB)^2(C^2 + 2\cos 2\beta)]$ (1) With A and β according to Carter for antennae $\frac{1}{2}\lambda$ in length.

2 ---- $[1 + 2ABC\cos(\alpha+\beta) + (AB)^2(C^2 + 2\cos 2\beta)]$ (2) With A and β according to Hertz for antennae of negligible length.

3 – – – $[1 + 2ABC\cos(\alpha+\beta)]$ . . . . (3) With A and β as for (1) but neglecting multiple reflections.

• • + + Experimental values of $({}_PI_0/{}_PI_0')^2$

of equation (3*a*) in which the values of A and β in the expression $[1-2ABC\cos\beta + (ABC)^2]^{-1}$ have been calculated from Carter's theory, using Tani's tables for antennae of length equal to $\lambda/2$. The dotted graph is also from equation (3*a*), but the values of A and β are those used by Palmer and Honeyball, based on Hertz's dipole theory which assumes the antennae to be of negligible length (see page 425). The "dashed" graph neglects multiple reflections, and the ordinates have been calculated from $[1 + 2ABC\cos\beta + (ABC)^2]$, which expression is obtained by taking only the first two terms of the original series.

In Fig. 3 it may be noted that the current ratios for values of D/λ as small as $0{\cdot}13$ agree to within the errors of experiment with the theoretical full-line graph. This

these latter figures the full-line curves are the graphical representations of equations (5), in which Tani's values of A and β are used; and the dotted graphs are also calculated from equations (5) but with the values of A and β deduced from the dipole theory of Hertz. The "dashed" graphs are based on the assumption that multiple reflections are negligible in their effect on the currents ${}_PI$ or ${}_QI$.

Because of the curious deviation of certain points (marked with a cross in Figs. 4, 5, 6, and 7) from the theoretical curves for values of D/λ less than about $0{\cdot}2$, it was thought advisable to check the data for this orientation of the antennae and plot the results in

* Owing to a calibration variation the value of ${}_QI_0'$ was found to be 2 % too high. The experimental points in Figs. 6 and 7 have been corrected accordingly.

accordance with equation (7) in which, since $\theta = 0°$, the right-hand side reduces to $4AB \sin(2\pi D/\lambda) \sin\beta$. It is significant that no such deviation occurs for small values

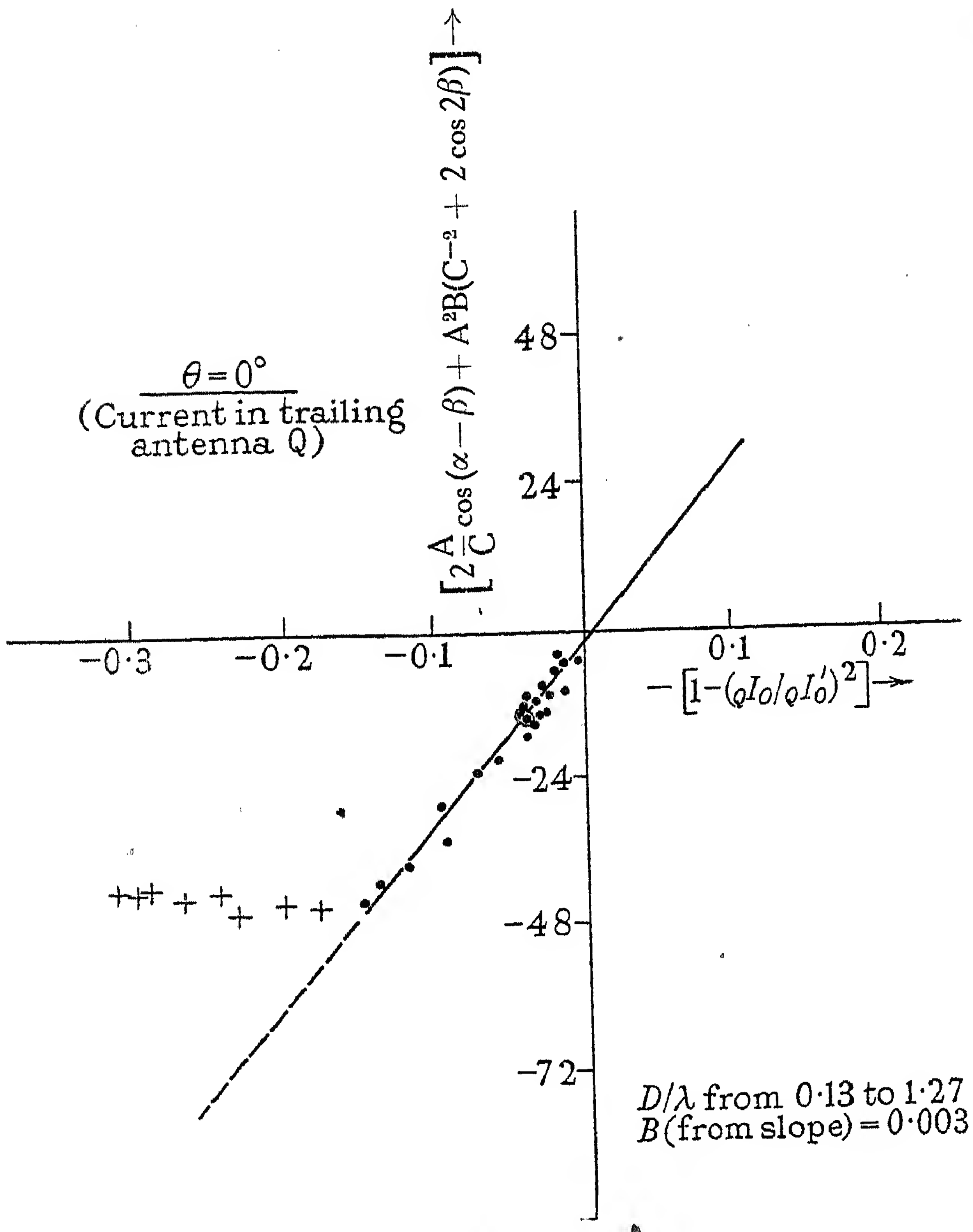

Fig. 6

vary from D/λ equal to 0·30–0·80. The curious deviations noted above for small values of D/λ are here definitely confirmed.

(iii) Antennae with the plane containing them oriented at any angle to the direction of wave propagation.

Finally, experiments with the antennae revolving (variable θ) were carried out for four constant values of D/λ, viz. 0·50, 0·42, 0·38, and 0·22. The results are calculated according to equation (7) (using $B = 0{\cdot}003$ as deduced from Figs. 4 and 6) and are shown as a linear graph in Fig. 9 and as polar diagrams in Fig. 10. In this latter figure the radii vectores are proportional to the current amplitude ${}_PI_0$. The signficance of the divergence from the theoretical graphs of most of the experimental points marked with a cross, for which D/λ is equal to 0·22, is discussed below.

(4) CONCLUSION

From the linearity of the graphs shown in Figs. 2, 4, 6, 8, and 9, it may be concluded that the currents in two parallel tuned receiving antennae would vary with the antenna spacing (i.e. with D/λ) and with the orientation of the plane containing the aerials (i.e. with θ) in the manner indicated by equations (2), (4), and (6), when situated in a uniform radiation field, and vary in accordance with equations (3), (5), and (7), when in a non-uniform field. But from the deviations for small values of D/λ shown by the points marked with a cross in Figs. 4 to 8 for which $\theta = 0°$, it is evident that the theoretical equations are not applicable to values of D/λ less than about 0·25 when the line joining the antennae passes through the transmitter. Furthermore, by considering the divergence of the points marked with a cross in Figs. 9

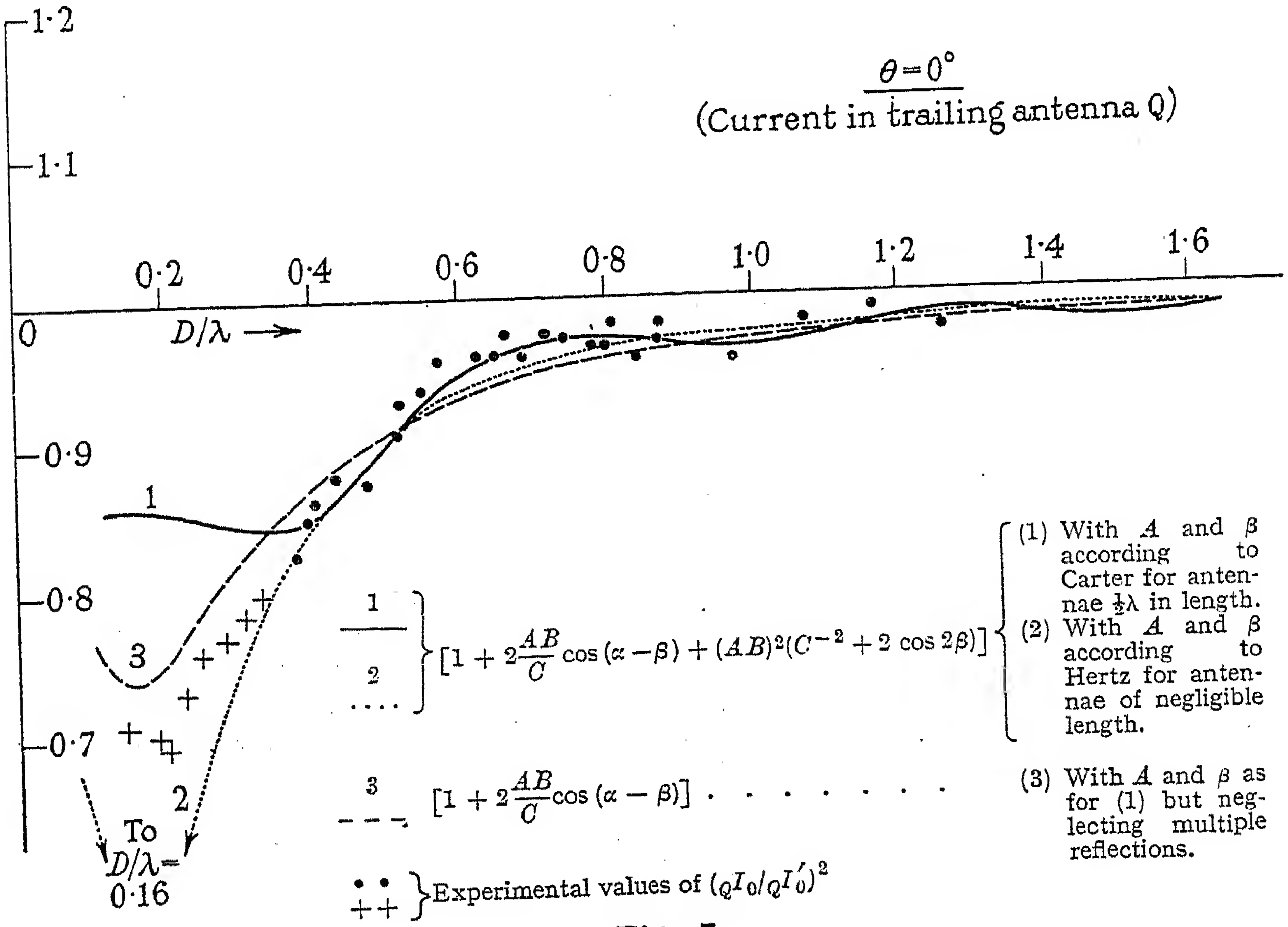

Fig. 7

of D/λ in Figs. 2 and 3, for which $\theta = 90°$. The 12 points marked with a cross in Fig. 8 were obtained for values of D/λ ranging from 0·13 to 0·30. The other 21 points and 10 it is apparent that the foregoing theory applies to the currents in parallel antennae *which are close together* (i.e. small D/λ) only when the line joining them is more or

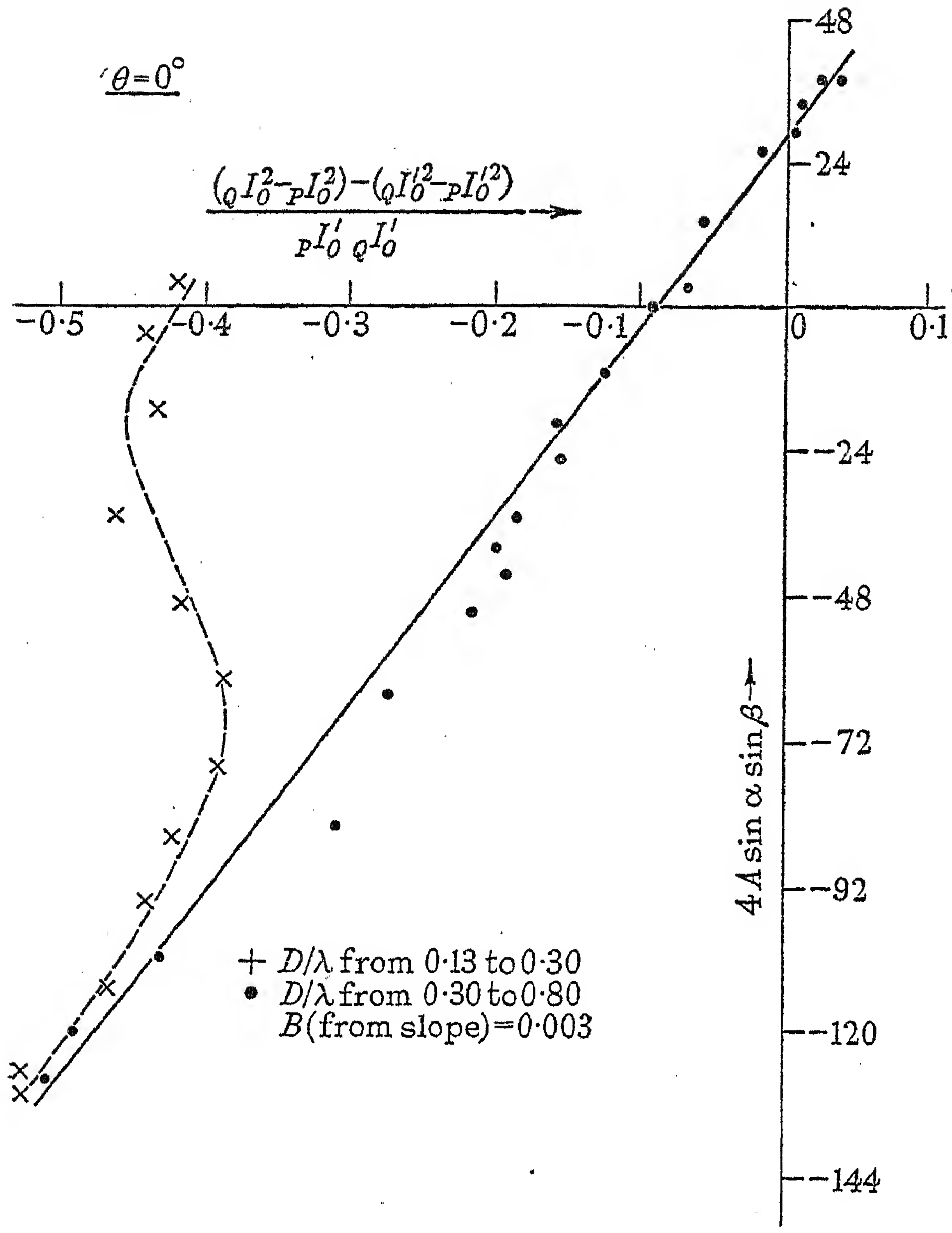

Fig. 8

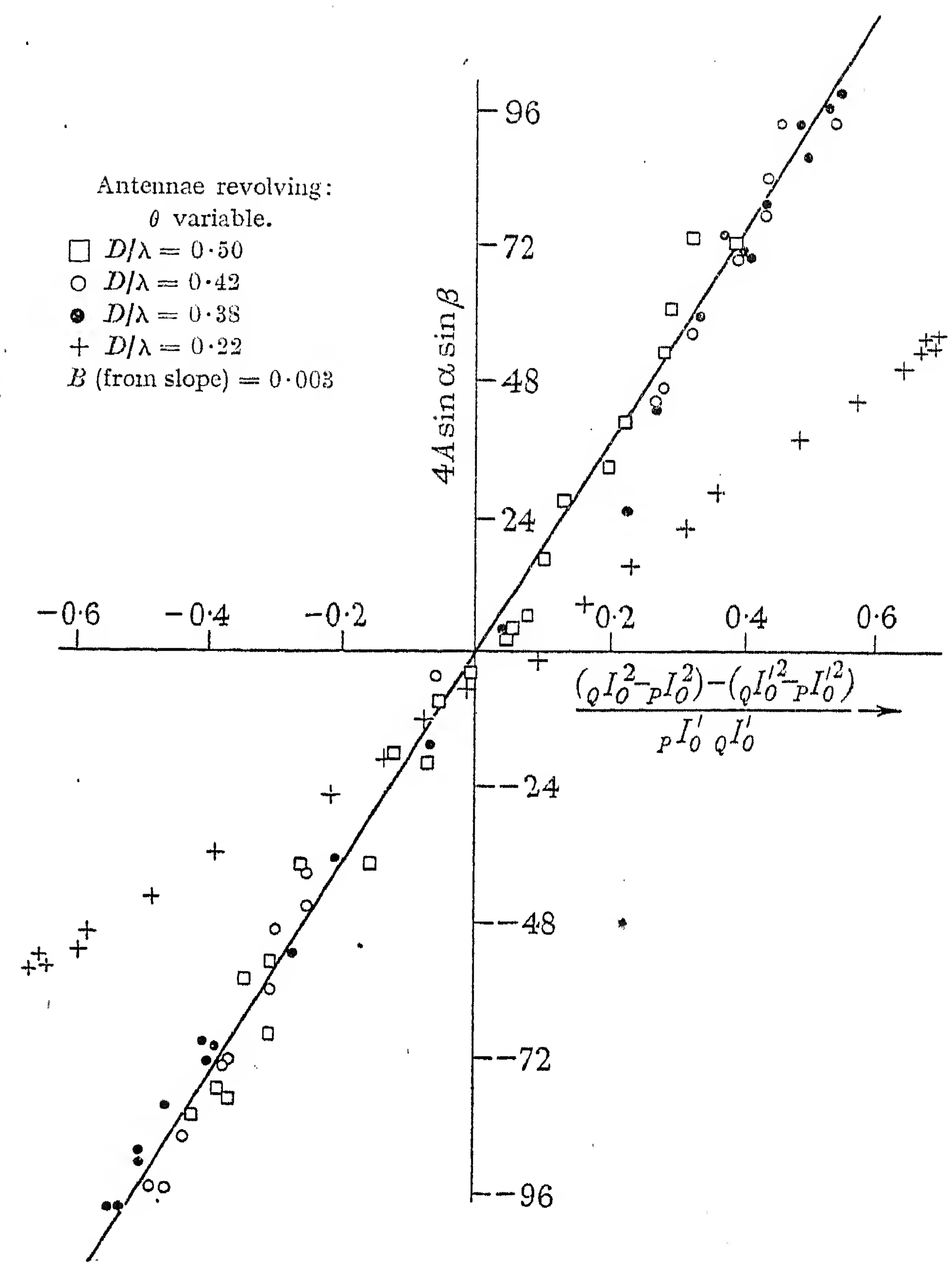

Fig. 9

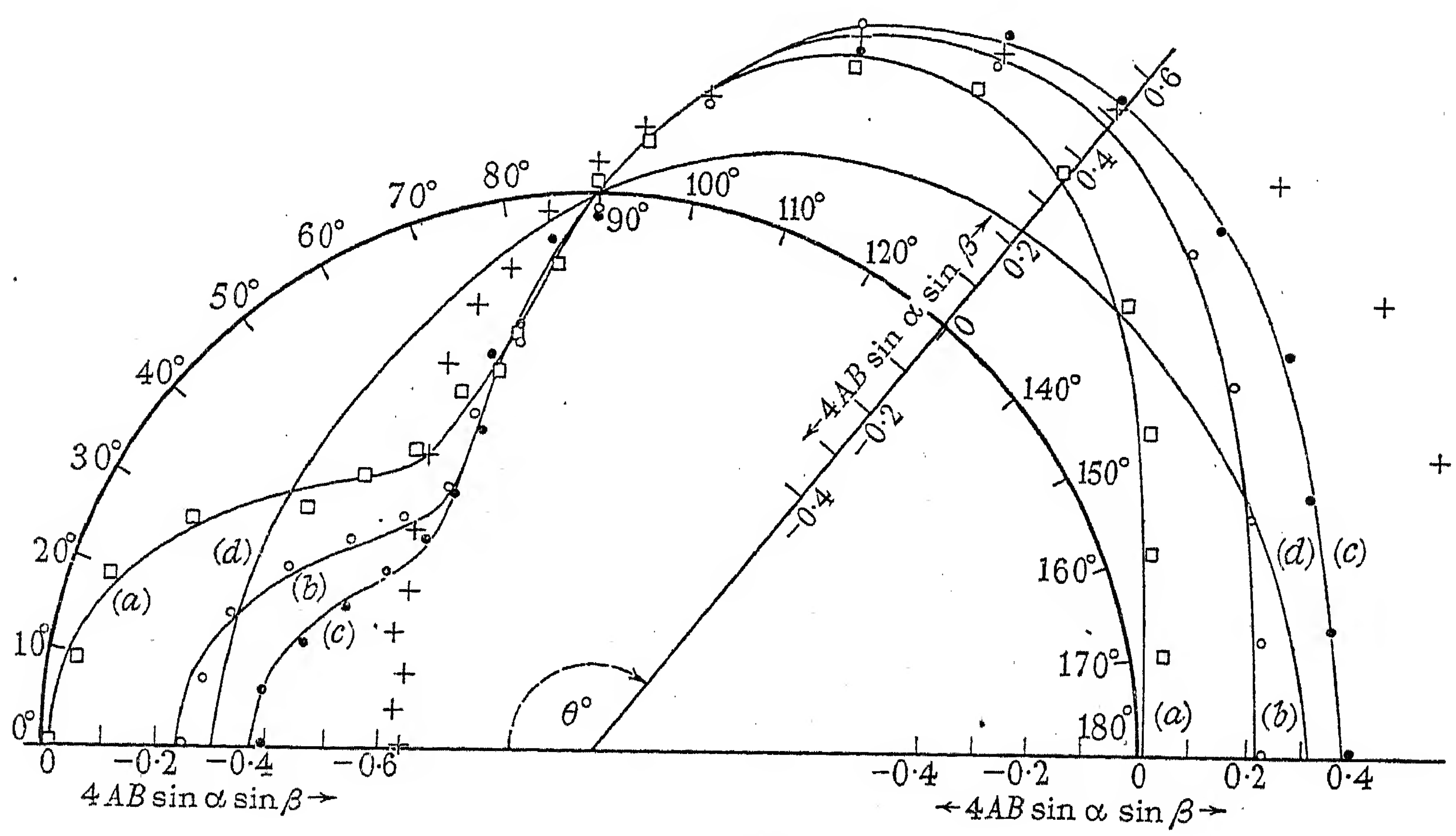

Fig. 10

(a) —— □ —— $D/\lambda = 0{\cdot}50$
(b) —— ○ —— $D/\lambda = 0{\cdot}42$
(c) —— ● —— $D/\lambda = 0{\cdot}38$
(d) —— + —— $D/\lambda = 0{\cdot}22$

Experimental points are:—
$$\frac{({}_QI_0^2 - {}_PI_0^2) - ({}_QI_0'^2 - {}_PI_0'^2)}{{}_PI'_0\,{}_QI'_0}$$

less perpendicular to the direction of wave propagation (i.e. $\theta \simeq 90°$). This follows from the fact that the points marked with a cross in Fig. 9 only coincide with the straight line at the origin, where $\theta = 90°$, whilst in Fig. 10 such points are near the curve (d) only in the neighbourhood of 90°. In other words some unconsidered effect is operative when the antennae are close together and the line joining them is not perpendicular to the direction of wave propagation. It seems probable that, with these particular conditions, the assumption that the presence of one antenna does not affect the field produced by the transmitter in the neighbourhood of the other is not true. A comparison of the points marked with a cross in Figs. 5 and 7 shows that the current in the leading antenna P is abnormally increased at the expense of the current in the trailing antenna Q.

field in the neighbourhood of the other, and (iv) the variations in the received currents with changes in the ratio D/λ and with the orientation θ are given by equations (4) and (6) when the radiation field is uniform, and by equations (5) and (7) when the field is not uniform.

REFERENCES

(1) M. Abraham: "Theoretical Investigation on the Radiation from Antenna Systems," *Archiv für Elektrotechnik*, 1919, vol. 8, p. 92.

(2) M. B. Bruewitsch: "The Radiation from Complex Antennae with Identical Elements," *Annalen der Physik*, 1926, vol. 81, p. 425.

(3) R. M. Wilmotte and J. S. McPetrie: "Theoretical Investigation of the Phase Relations in Beam Systems," *Journal I.E.E.*, 1928, vol. 66, p. 949.

Table

Critical Values of D/λ for Two Parallel Tuned Antennae

References:	Englund and Crawford* 1929	Palmer and Honeyball† 1929	Carter‡ 1932	Palmer and Taylor§ 1935	Brown‖ 1937	Figs. 5 and 3 of present paper 1937	
For max. current	0·32 0·85	0·33 0·86	— —	0·316 0·856	0·15 0·80	0·31 0·85 1·36 1·87	for $\theta = 0°$
For min. current	0·60	0·60	—	—	0·59	0·58 1·10 1·61	
For max. currents	0·71	0·71	0·69	0·694	0·68 1·75 2·79	0·67 1·71	for $\theta = 90°$
For min. currents	1·22	—	1·31	—	1·21 2·23	1·20	

* See Reference (10). † *Ibid.*, (11). ‡ *Ibid.*, (6). § *Ibid.*, (12). ‖ *Ibid.*, (9).

Fig. 3 shows the optimum antenna spacings for maximum and minimum currents with idle or parasitic antennae, when the plane containing the antenna is perpendicular to the direction of wave propagation; whilst Fig. 5 gives similar information for the leading antenna when the plane containing the antennae is parallel to the direction of wave propagation. The critical values of D/λ from these figures are compared in the Table above with the values obtained by previous authorities.

With the exception of the smallest value of D/λ for $\theta = 0°$, it is apparent that the differences between the various theoretical treatments are, on the whole, less than the errors of experiment when measurements of the critical values of D/λ are made at ultra-high frequencies. Consequently, at these frequencies and with antennae not closer than $0{\cdot}25\lambda$, unless $\theta = 90°$, it is concluded that (i) tuned half-wave receiving antennae may be considered to act as Hertzian dipoles, (ii) multiple reflections have little effect in determining optimum antenna spacings but have a more marked effect on current magnitudes, (iii) either antenna does not appreciably affect the incident

(4) A. A. Pistolkors: "The Radiation Resistance of Beam Antennas," *Proceedings of the Institute of Radio Engineers*, 1929, vol. 17, p. 562.

(5) R. Beckmann: "On the Theory of Radiation Coupling in a Short-wave Antenna System," *Annalen der Physik*, 1930, vol. 4, p. 829; and "Calculation of Radiation Characteristics and Radiation Resistance of Antenna Systems," *Zeitschrift für Hochfrequenztechnik*, 1930, vol. 36, pp. 182 and 201.

(6) P. S. Carter: "Circuit Relations in Radiating Systems and Application to Antenna Problems," *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20. p. 1004.

(7) K. Tani: "Theory of the Complex Antenna," *Report of Radio Research in Japan*, 1933, vol. 3, p. 19.

(8) G. H. Brown and R. King: "High-frequency Models in Antenna Investigations," *Proceedings of the Institute of Radio Engineers*, 1934, vol. 22, p. 457.

(9) G. H. Brown: "Directional Antennas," *ibid.*, 1937, vol. 25, p. 78.
(10) E. C. Englund and A. B. Crawford: "The Mutual Impedance between Adjacent Antennas," *ibid.*, 1929, vol. 17, p. 1277.
(11) L. S. Palmer and L. L. K. Honeyball: "The Action of a Reflecting Antenna," *Journal I.E.E.*, 1929, vol. 67, p. 1045.
(12) L. S. Palmer and Dennis Taylor: "On a theory of the Action of Rectangular Short-wave Frame Aerials," *Proceedings of the Physical Society*, 1935, vol. 47, p. 377.
(13) L. S. Palmer and K. G. Gillard: "The Distribution of Ultra-high-frequency Currents in Long Transmitting and Receiving Antennae," *Journal I.E.E.*, 1938, vol. 83, p. 415.
(14) L. S. Palmer and Dennis Taylor: "The Action of a Tuned Rectangular Frame Aerial when Transmitting Short Waves," *Proceedings of the Physical Society*, 1934, vol. 46, p. 62.

DISCUSSION ON "THERMAL FLUCTUATIONS IN COMPLEX NETWORKS"*

Mr. D. A. Bell (*communicated*): I believe that the analysis given in Appendix 1 of the paper can be made of even greater generality by a very slight change in the handling of the transfer impedances.

Since I have indicated in a recent paper† that the fundamental property of a pure resistance is probably the generation of the fluctuation current

$$\overline{I}^2 = \frac{4kT}{R}df \quad . \quad . \quad . \quad . \quad . \quad (A)$$

rather than the voltage $\overline{V}^2 = 4RkTdf$, it is interesting to repeat the analysis in terms of a fluctuation current in place of voltage. In order to avoid confusion with the author's notation, while using his Fig. 11, the letter N with suitable suffixes will be used to represent various impedances, defined as follows:—

(1) Let N_{Ax} be equal to the p.d. between the points A and A′ (on open circuit externally) per unit current in r_x.

(2) Let $N_{AA'}$ be the internal impedance between A and A′, i.e. the p.d. between A and A′ per unit current injected from a generator connected between these two points.

(3) Let $1/N_{xA}$ be equal to the current in r_x per unit p.d. across AA′, i.e. N_{xA} is the impedance from A to x corresponding to the impedance N_{Ax} from x to A.

Assuming an input mean square current i_x^2 flowing in r_x, we then have an output mean-square voltage across AA′ given by

$$|v^2_{AA'}| = N^2_{Ax} i^2_x$$

and, using equation (A),

$$|v^2_{AA'}| = N^2_{Ax} \cdot \frac{4kT_x}{r_x}df$$

$$\therefore \quad |i^2_{AA'}| = \frac{|v^2_{AA'}|}{N^2_{AA'}} = \frac{4kdf}{N^2_{AA'}} \cdot \frac{N^2_{Ax}T_x}{r_x}$$

For a number of resistive elements r_x within the network, the resultant mean square fluctuation current between A and A′ will be

$$|I^2_{AA'}| = \frac{|V^2_{AA'}|}{N^2_{AA'}} = \frac{4kdf}{N^2_{AA'}} \cdot \sum \frac{N^2_{Ax}T_x}{r_x} \quad . \quad . \quad (B)$$

Now let a current i_0 from an external generator be injected throughout the points A, A′. The mean square current in r_x will then be

$$|i^2_x| = \frac{E^2_{AA'}}{N^2_{xA}} = \frac{i^2_0 N^2_{AA'}}{N^2_{xA}}$$

and the power dissipated therein is

$$|i^2_x| r_x = \frac{r_x i^2_0 N^2_{AA'}}{N^2_{xA'}} \quad . \quad . \quad . \quad . \quad (C)$$

But if the input impedance $N_{AA'}$ as viewed from the external generator is made up of resistive and reactive components in series, $m + jn$, the power absorbed from the generator will be $i^2_0 m$. Comparing this with the power dissipation given by equation (C), we find that

$$m = \frac{r_x N^2_{AA'}}{N^2_{xA}}$$

or, in the general case of many resistive elements,

$$|m| = N^2_{AA'} \sum \frac{r_x}{N^2_{xA}} \quad . \quad . \quad . \quad . \quad (D)$$

Comparing equations (B) and (D), we find that, provided $N^2_{Ax} = N^2_{xA}$,

$$|I^2_{AA'}| = 4kdf \sum \frac{T_x}{m_x}$$

corresponding exactly to the result obtained by the author in the analysis based on fluctuation voltage.

Now he demanded, as necessary for the validity of his analysis, the condition $Z_{Ax} = Z_{xA}$, and therefore limited himself to linear networks. But, as presented above (and the same could be shown to be true of the author's analysis), the necessary condition is a relationship between squares of impedances, $N^2_{Ax} = N^2_{xA}$, and it appears that this must be satisfied even by non-linear networks. For consider the system shown in Fig. A, where two equal resistances R at the same temperature T are joined respectively to pairs of terminals 1 and 2 of a non-linear impedance supposed to be such that $Z_{12} \neq Z_{21}$, but both Z_{12} and Z_{21} are large compared with R. Now, on any hypothesis, two equal resistances at the same temperature will generate equal apparent fluctuation voltages,

* Paper by Dr. F. C. Williams (see vol. 81, p. 751).
† "A Theory of Fluctuation Noise," *Journal I.E.E.*, 1938, vol. 82, p. 522.

say of mean-square value V^2. Then, since Z is large compared with R, the two currents flowing in the circuit are approximately

$$I_{12}^2 = V^2/Z_{12}^2$$

$$I_{21}^2 = V^2/Z_{21}^2$$

The amounts of energy transferred from resistance 1 to resistance 2 and from resistance 2 to resistance 1 are then

$$\left.\begin{aligned} W_{12} &= RI_{12}^2 = RV^2/Z_{12}^2 \\ W_{21} &= RI_{21}^2 = RV^2/Z_{21}^2 \end{aligned}\right\} \quad . \quad . \quad . \quad \text{(E)}$$

But unless $W_{21} = W_{12}$ the resistance receiving the greater amount of energy will rise in temperature, and heat will then be transferred in a self-acting system from a body at a lower temperature to one at a higher temperature. This, however, is contrary to the second law of thermodynamics* and is thus impossible. Therefore, from the

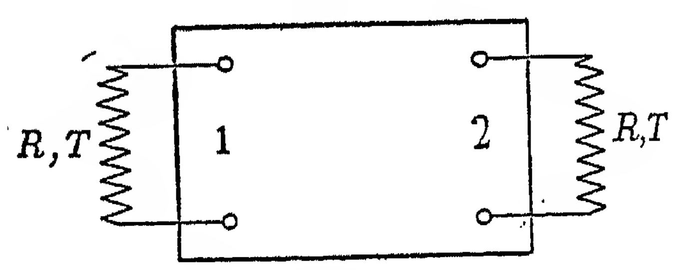

Fig. A

necessity of equating W_{12} and W_{21} in equations (E), we are compelled to put

$$Z_{12}^2 = Z_{21}^2$$

It follows that the theorem proved by the author, that the fluctuation voltage at the terminals of a complex network is of magnitude corresponding to the resistive component of the impedance as viewed from the terminals, is also true of non-linear systems, provided only that the resistive component of the impedance is calculated in terms of power dissipation. I have already discussed the application of this principle to the thermionic valve (in the paper quoted above); but is it not also possible that the iron-cored coil, for which experimental figures are given in Fig. 8 of the present paper, was in fact a non-linear system if hysteresis losses were appreciable? It would be interesting to try the experiment on a more thoroughly non-linear device, e.g. an iron-cored coil without air-gap, and perhaps with a suitable polarizing current. In such cases, where it is necessary to discriminate against harmonics, the resistive component of the input impedance could probably be measured better by a milliammeter and dynamometer method than by the three-voltmeter method.

Dr. F. C. Williams (*in reply*): Mr. Bell's proposal of a theorem in terms of a "current representation" of fluctuations comparable with that given in the paper in terms of a "voltage representation" is of considerable interest. The idea is not new,† but has never been fully discussed. I cannot agree, however, that Mr. Bell's analysis is equivalent to that developed in the paper. His analysis leading to equation (D) is a repetition of Appendix 2, and comparison of the notations in the resulting equations shows that

$$|m| \equiv r; \quad N_{AA'}^2 \equiv Z_{AA'}^2; \quad N_{Ax}^2 \equiv Z_{Ax}^2$$

From Mr. Bell's equation (B),

$$\overline{V}_{AA'}^2 = 4kdf \sum \frac{N_{Ax}^2 T_x}{r_x}$$

But, expressing equation (2) of the paper in Mr. Bell's notation by means of the identities given above,

$$\overline{V}_{AA'}^2 = N_{AA'}^2 4kdf \sum \frac{r_x T_x}{N_{xA}^2}$$

These two expressions for $\overline{V}_{AA'}^2$ are not equivalent.*

The discrepancy is thought to be due to a fundamental error in Mr. Bell's interpretation of equation (A). He states that a resistance R generates a current of mean square value defined by equation (A), and it appears from his definition of N_{Ax} that this current is supposed to flow always in R, whether R is connected to a network or not; he apparently identifies $\overline{I}^2$ with the thermal motion of free electrons in R. In my view, equation (A) defines a current supplied to R by a hypothetical generator connected in parallel with R. In such circumstances $\overline{I}^2$ flows partly in R and partly in the network to which R is connected. Also, $\overline{I}^2$ then bears no relation to the actual motion of free electrons and is merely a mathematical tool which assists computation; it is no more fundamental than is the "voltage representation" given in the paper. These views are fully set out in a paper at present in course of preparation, and need not be further discussed here, except to note that a "current representation" based on them has been developed which yields results consistent with those obtained by "voltage representation."

The limitation of the analysis to linear networks does not depend only on the requirement that $Z_{Ax}^2 = Z_{xA}^2$, for the summation leading to equation (2) assumes that the mean square value of the sum of a number of fluctation currents is the sum of their mean-square values, and such is not necessarily true in non-linear networks. Further, it is not usually possible to specify impedance values in non-linear networks: the "impedance" then depends in general on the amplitude and wave-form of the applied e.m.f. and on the presence or otherwise of other e.m.f.'s in the network. Thus, despite Mr. Bell's ingenious proof that Z_{12}^2 is always equal to Z_{21}^2 (since both can vary with time in non-linear networks, this should perhaps be stated: average Z_{12}^2 = average Z_{21}^2), it is still thought necessary to restrict the analysis to linear networks. The limitation of scope involved appears small, since there are but few common circuit-elements which respond in a markedly non-linear manner to the exceedingly small currents and potentials associated with fluctuation phenomena.

* That is to say, it would be a system in which "perpetual motion" could be obtained by utilizing the self-maintaining difference of temperature to drive a heat engine.

† *Journal I.E.E.*, 1936, vol. 79, p. 349.

* It can be shown that, as defined by Bell, N_{xA} is not equal to N_{Ax}.

REGULATIONS FOR CONTROLLING THE EARTHING OF ELECTRICAL INSTALLATIONS TO METAL WATER-PIPES AND WATER-MAINS*

DRAWN UP AND APPROVED BY

THE INSTITUTION OF CIVIL ENGINEERS, THE INSTITUTION OF ELECTRICAL ENGINEERS, THE INSTITUTION OF WATER ENGINEERS, THE BRITISH WATERWORKS ASSOCIATION, AND THE WATER COMPANIES' ASSOCIATION

INTRODUCTION

It has for many years been a common practice to utilize incoming water-mains for the earthing of electrical installations.† Cases have arisen, however, where corrosion of water-mains has been attributed to such earthing. It is known, for example, that continuous current causes electrolytic corrosion where it leaves a metal conductor or pipe to enter the earth, but the effect of the passage of alternating current to earth is somewhat obscure. A further point in connection with earthing is that there have been instances where electric shocks have been incurred during the repair of water-mains.

It was obvious that some agreement as to the conditions under which earthing-connections should be made was desirable, and the question was considered by a Joint Committee of The Institution of Electrical Engineers and the Metropolitan Water Board, as a result of which a draft memorandum on Earthing to Water-Mains was issued on the 20th December, 1926. It was not possible, however, to conclude the negotiations on that occasion.

The need for such agreement became increasingly evident, and it was in these circumstances that a Sub-Committee of The Institution of Civil Engineers Research Committee was formed in March, 1936, to explore the problem of possible injury to metal water-pipes and mains through the earthing thereto of electrical installations, particularly in relation to alternating currents, with a view to

(*a*) investigating the existence and extent of such injury, research being carried out if necessary;

(*b*) obtaining mutual agreement on the conditions under which earthing-connections to metal water-pipes and water-mains might be made; and

(*c*) if necessary, formulating a set of regulations in respect thereof.

The Sub-Committee includes nominees of The Institution of Electrical Engineers, The Institution of Water Engineers, the British Waterworks Association, and the Water Companies' Association, and acknowledgment is here made of the valuable assistance which they have rendered.

The Sub-Committee have taken into consideration the memorandum drawn up by the above Joint Committee, and they have been successful in securing unanimous agreement on the conditions under which earthing-connections may be made in recommending the following Regulations in respect thereof.

The Regulations are intended to be applicable generally, with one exception: Post Office installations other than those for power and lighting services are excluded from the application of these Regulations, but are subject to agreement between the authorities concerned.

In the course of their work the Sub-Committee came to the conclusion that there were certain other aspects of the problem which could with advantage form the basis of research. The Institution gratefully acknowledges the funds which have been subscribed for such research by the interests concerned, and the investigation has been undertaken by the British Electrical and Allied Industries Research Association. The programme of research so far approved is as follows:—

(i) The amount and effect of aggregate leakage-currents on water-pipes.

(ii) The possibility of partial rectification of alternating currents in underground water-supply systems (*a*) at earthing-connections; (*b*) between metal pipes and the soil.

(iii) The possibility of primary-cell effects in water-supply systems.

(iv) The relation of the above to the question of corrosion.

REGULATIONS

Preamble.

These Regulations have been drafted under the auspices of The Institution of Civil Engineers as the result of agreement come to between representatives of water and electrical interests. They are subject to any amendment which may be shown to be desirable as a result of further experience or research.

Clause 1.

An earth-wire connecting an electrical installation to a water-main or water-pipe is to be used only:—

(*a*) as a measure of safety for the purpose of returning to the source of supply such leakage current as may flow, or result from a failure of insulation.

(*b*) for radio-frequency currents and those from radio-interference-suppression devices.

Clause 2.

A water-main or water-pipe shall not be cut, drilled or broken, for purposes of Clause 1, and all reasonable and proper care shall be exercised, in making any earth-connection, to prevent injury or damage to a water-main or water-pipe.

* Published by The Institution of Civil Engineers. Copies can be obtained from Messrs. William Clowes and Sons, Ltd., 94 Jermyn Street, S.W.1, price 6d. each, post free.

† As defined by the Electricity Supply Regulations, 1937, for Securing the Safety of the Public . . . Clause 29 (*a*) (*i*): i.e. All metal work enclosing supporting or associated with the consumer's installation, other than that designed to serve as a conductor.

Clause 3.

Every earth-connecting device to a water-main or water-pipe shall be of such an approved design* as to ensure an efficient electrical connection, and other than as provided for in Clause 4 shall be attached in a position convenient for, and easy of, access.

Clause 4.

An earth-connection shall only be made to a buried water-main or water-pipe after notice to, and in a manner approved by, the water authority concerned.

Clause 5.

Wherever an earth-connection is made to a water-main or water-pipe on any premises in which is installed a water-meter, a proper, sufficient, and suitable bond shall in all such cases be placed across such water-meter by the user of the meter, free of expense to the water-authority.

Clause 6.

Where the water-supply authority has reason to believe that damage to water-mains or water-pipes is being caused by an excessive flow of current from an earth-connection made to a water-main or water-pipe they shall, in general, request the electricity-supply undertakers for the district to test the installation, arrangements being made for a representative of the water-supply authority to be present at the time the test is made. If, however, for any reason the water-supply authority should desire to test for electrical leakage from an installation to water-mains or water-pipes, that authority will be at liberty to make such test after advising the electricity-supply undertakers for the district of their intention, giving such notice to the consumer as may be necessary, and inviting the presence of a representative of the electrical undertakers when the test is made.

Water-supply authorities (whilst maintaining the powers which they are advised are conferred by existing water-supply legislation to enter premises, and if necessary to test for electrical leakage) agree that, in general, tests for electrical leakage, and any notice to the consumer which may be necessary in connection therewith, should be made and given by the electricity-supply undertakers, who will usually possess the better facilities.

NOTE.—Attention is drawn to the fact that in certain cases non-metallic water-pipes are in use, and the electrical implications of this should be recognized.

* For the purposes of Clause 3 the approval of the design of the earth-connecting device should rest with a joint committee of electrical and water representatives.

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INSTITUTION NOTES

PARSONS ANNUAL MEMORIAL LECTURE

The third Parsons Memorial Lecture will, at the invitation of the Royal Society, be given in 1938 under the aegis of The Institution of Mechanical Engineers, who have arranged for the lecture on this occasion to be delivered by Mr. Stanley S. Cook, F.R.S. (of the Parsons Marine Steam Turbine Co.). The Lecture, entitled "Sir Charles Parsons and Marine Propulsion," will be delivered in the building of The Institution of Mechanical Engineers, at Storey's Gate, Westminster, S.W.1, on Friday, 2nd December, 1938. A general invitation has been extended for I.E.E. members to attend, but it may be necessary for those desiring to be present to obtain tickets of admission. A further announcement, giving final details, will therefore be made in these Notes nearer the date of the meeting.

[*Note:* The first lecture was delivered by Sir Frank Smith in 1936 before the N.E. Coast Institution of Engineers and Shipbuilders, and the second, in 1937, by Dr. Gerald Stoney before the I.E.E. (see *Journal*, 1938, vol. 82, p. 248).]

PROCEEDINGS OF THE HIGH-TENSION CONFERENCE, PARIS

The Proceedings (in French) of the 1937 Session of the Conference have now been published. They comprise three bound volumes containing, in all, 3 000 pages. The volumes deal respectively with (1) Generation, transformation, and circuit-breaking; (2) Construction, insulation, and maintenance of overhead and underground networks; (3) Operation, protection, and interconnection of networks.

Copies of the Proceedings can be obtained from the Secretary of the Conference, 54 Avenue Marceau, Paris, price 450 francs.

JOINT COMMITTEE ON MATERIALS AND THEIR TESTING

The Joint Committee on Materials and their Testing is organizing a meeting which will be held on the 25th November next under the auspices of The Institution of Electrical Engineers for the discussion of the subject of Non-destructive Testing. The subject has been divided into three sections, namely, magnetic and electrical methods, X-rays and gamma rays, acoustical and general methods; and each section will be dealt with by authors representing respectively Great Britain, the Continent of Europe, and the United States. Thus, magnetic and electrical methods will be dealt with in papers by Dr. B. Berthold (director of the Reichs-Rontgenstelle, Berlin) and by Dr. A. P. M. Fleming, C.B.E., and Mr. B. G. Churcher; X-rays and gamma rays will be dealt with by Ing. J. E. de Graaf (of Philips's Gloeilampenfabrieken, Holland) and Dr. V. E. Pullin; while acoustical and general methods will be dealt with by Prof. Dr. Koster (of the Kaiser-Wilhelm-Institut für Metallforschung, Stuttgart) and Dr. S. F. Dorey. The experience and views of the United States of America will be presented in a joint paper by Mr. N. L. Mochel (metallurgical engineer, Westinghouse Electric and Manufacturing Co., Philadelphia), Mr. H. H. Lester (senior physicist, Watertown Arsenal, Watertown, Mass.), and Mr. R. L. Sanford (chief of the magnetic section, National Bureau of Standards, Washington).

In view of the authority of the authors contributing the papers, and of the very topical interest of the subject of Non-destructive Testing, it is expected that the meeting will be of considerable importance. It will be presided over by Dr. A. P. M. Fleming, C.B.E., President of The Institution of Electrical Engineers, and a general invitation to attend is extended to all those who are interested. Further details will be published later.

CONVERSAZIONE OF OVERSEAS MEMBERS

A Conversazione of members from overseas and their ladies was held in the Institution building on Thursday evening, 16th June, the attendance being about 130. The proceedings were opened by the President (Sir George Lee, O.B.E., M.C.) supported by the Council. Short addresses by Mr. H. Nimmo on " Electricity in Burma," and by Major B. Binyon, O.B.E., M.A., on " Accelerated Motion Cinematography in Natural Colours " (illustrated by a cinematograph film), followed in the Lecture Theatre. A reunion then took place in the Library, where the apparatus used in making his film was demonstrated by Major Binyon.

The following members temporarily in England from overseas were present: P. D. Abbott (Straits Settlements), L. S. Anand (India), R. Beck, Dipl. Ing. (Hungary), C. R. Bland (India), T. A. Brown (South Africa), B. F. Browne (Brazil), H. S. Bulley (India), R. L. Chantrill, B.Sc.(Eng.) (India), J. S. B. Colombi (China), M. Dunlop (India), E. Elton, B.Sc. (India), L. B. Harmer (China), A. T. Harpham (Southern Rhodesia), D. H. P. Henderson (India), H. C. Hitchcock, B.E. (New Zealand), E. J. Hogben, M.A. (India), A. G. Hughes (Burma), A. W. Johnstone, B.Sc.(Eng.) (Burma), A. D. Maclean, B.Sc.(Eng.) (Trinidad), D. H. Macnee, B.Sc. (Australia), C. H. Mellor (China), D. H. Melville (Malta), H. T. Moody (Burma), J. R. H. Morgan, B.E. (Australia), S. Mortimer (Straits Settlements), A. S. Phillips (China), H. P. Samuel, B.Sc. (Holland), A. J. Smith (New Zealand), C. S. Steel (India), T. L. Stephens, B.Sc.(Eng.) (Iran), D. M. Tombs, B.Sc.(Eng.) (New Zealand), H. E. Trent (U.S.A.), A. R. A. Tyrer (Aden), P. D. Webb (Burma), J. S. Whitney (China), and J. H. Wilson, M.C. (China).

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Passed*

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Atkinson, David.
Ballard, Walter George.
Barrett, Arthur Crabtree.
Barry, Dennis George Coode.
Bastin, Douglas James.
Bell-Francis, Trevor Rothwell.
Berge, Morris.
Buckle, George William Vincent.
Byrne, Denis Joseph.
Bywater, Kenneth Athorne Vallance.
Clark, Gilbert.
Collier, George Elder.
Darby, William Ernest.
Dark, Cyril Montague.
Ferguson, Ian Andrew.
Glyde, Thomas Charles William.
Grimes, Wilfred Wallace.
Hick, George.
Hollingworth, Stephen Ian.
Isaac, John Edward.
Jagger, Hubert.
James, George Anthony.
Meek, George Gilbert.
Miller, Jack.
Pagdin, Edward Houldin.
Patrick, Robert James.
Phillips, Alban William.
Robinson, Thomas Philip.
Rustin, Maurice Edward.
Stephenson, George William.
Thorpe, Eric.
Varcoe, Kingsley John.
Weaire, Reginald Frederick.
Wincott, Leslie Moreland.
Woods, John Victor.
Wylie, John Howard.

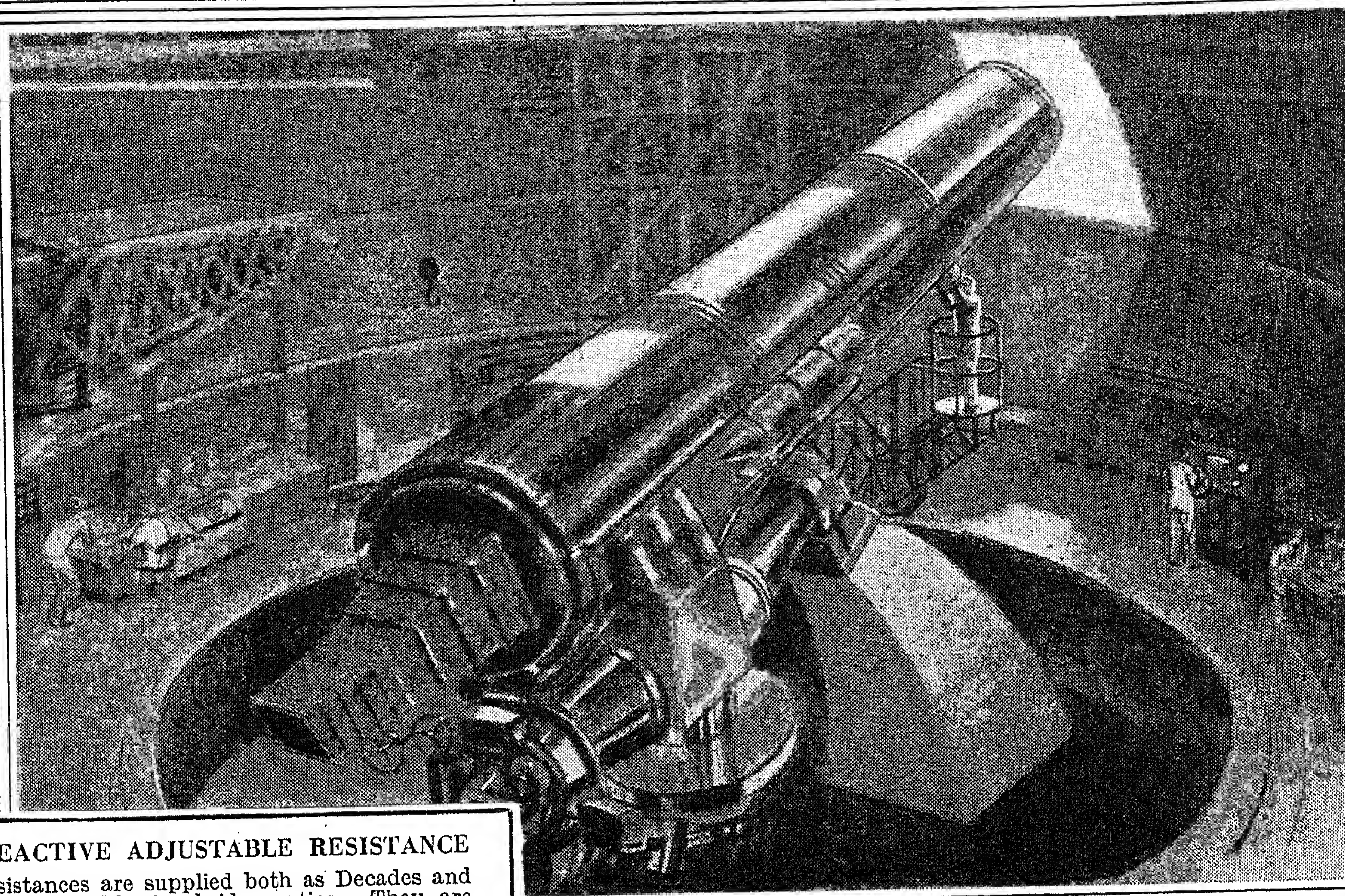
Passed PART I only

Belsey, Stuart Urquhart.
Collins, John Henry.
Davies, Roy Travers.
Ferguson, Oswald.
Gange, Hedley Gordon.
Meiklejohn, William Kenneth.
Mills, Eastall.
Owen, Albert James Arthur.
Rake, Charles Ernest Tudor.
Sigee, Eric.
Sutton, Peter.
Williams, Denis.

Passed PART II only

Brocklesby, Harry.
Coombs, Frederick Leslie.
Earl, John Wakelin.
Hampton, Arthur Edward.
Hitchen, Herbert.
McKenzie, Edgar Donald Murdoch.
Mohan, Anand Saroop.
Pearce, Albert John.
Richards, Sydney Bennett.
Shaw, Arthur Francis.
Sims, Eric Arthur.
Stevens, Stanley Walter.
Whaley, Norman Sheffield.
Wright, Albert Douglas.

* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.



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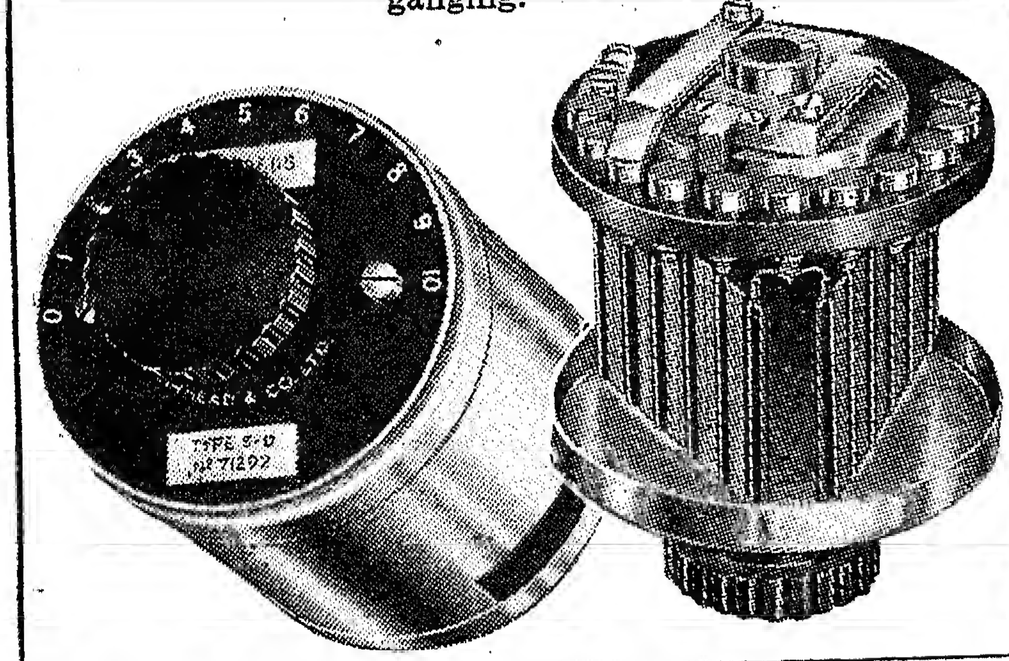

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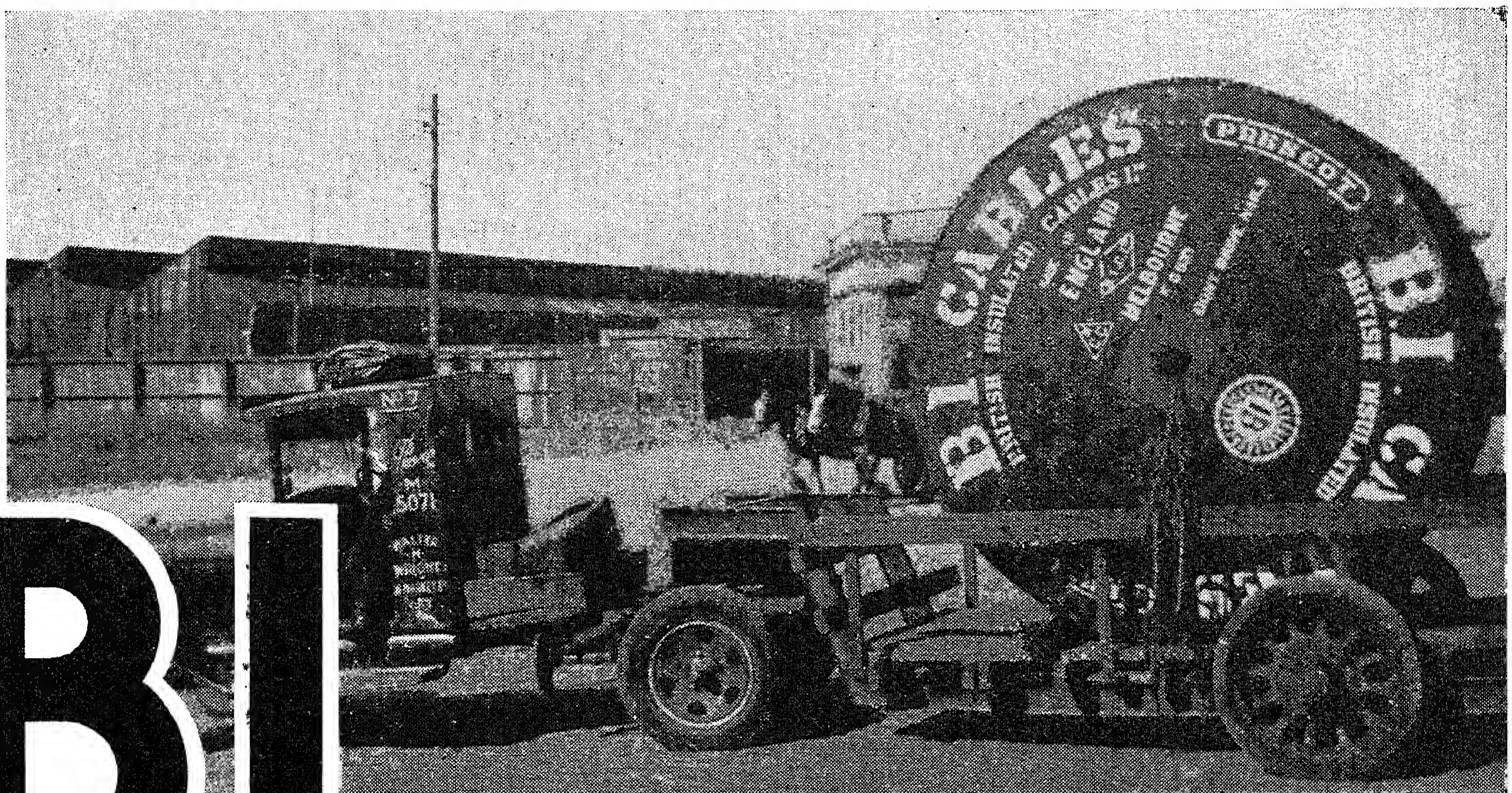

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